DAMES & MOORE JOB NO. 4010-088-06
Salt Lake City, Utah
March 23, 1983

EVALUATION OF HYDROLOGIC EFFECTS RESULTING FROM PIT BACKFILLING JACKPILE-PAGUATE URANIUM MINE, NEW MEXICO FOR ANACONDA MINERALS COMPANY

Dames & Moore

Dames & Moore

250 East Broadway, Suite 200
Salt Lake City, Utah 84111
(801) 521-9255
TWX: 910-925-5692 Cable address: DAMEMORE

March 29, 1983

Anaconda Minerals Company
New Mexico Operations
P.O. Box 638
Grants, New Mexico 87020

Attention: Mr. Meade Stirland

Gentlemen:

Transmitted herewith are thirty copies of our report "Evaluation of Hydrologic Effects Resulting From Pit Backfilling, Jackpile-Paguate Uranium Mine, New Mexico, For Anaconda Minerals Company."

We would appreciate the opportunity to perform this study for you. If you have any questions, please call us.

Yours very truly,

DAMES & MOORE

Larry T. Murdock
Partner

LTM/GWC:fl

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

TABLE

LIST OF PLATES

EXECUTIVE SUMMARY

This report presents our evaluation of long-term effects of pit backfilling upon recovered ground water table levels and water quality at the Jackpile-Paguate Uranium Mine. The following conclusions and recommendations have been made:

1. Planned backfill levels as presented in the Anaconda (1982) reclamation report should achieve or exceed the objective of being a minimum of three feet above the long-term water table in the backfilled pits except in the North Paguate pit.

2. It is recommended that select, low permeability materials be placed in the western part of the North Paguate pit to form an internal cut-off. This would control water levels to acceptable levels east of the cut-off. Backfill levels west of the cut-off should be increased to a minimum elevation of 5983 ft.

3. Ground water which enters the pit backfill during initial resaturation is expected to undergo significant increases in dissolved solids content, predominantly sulfate, sodium and calcium, due to leaching of oxidized materials. Subsequently, additional leaching is expected to rapidly decrease as dissolved oxygen is depleted. Uranium and radium-226 may locally exceed 5 mg/l and 30 pCi/l, respectively. Heavy metals, selenium, arsenic, and other trace constituents are expected to be within EID standards (EID standards are not necessarily applicable in a legal sense, but are untilized in this report for the purpose of comparison to reasonable use criteria). The pH of ground water in the pits is not expected to decrease below 6.0 units.

4. Negligible impact upon viable surface water and ground water resources as a result of movement of waters from the pits is expected.

EVALUATION OF HYDROLOGIC EFFECTS
RESULTING FROM PIT BACKFILLING
JACKPILE-PAGUATE URANIUM MINE, NEW MEXICO
FOR ANACONDA MINERALS COMPANY

INTRODUCTION

This report presents our evaluation of the long-range effects of pit backfilling upon water table recovery and ground water quality at the Jackpile-Paguate Uranium Mine, Cibola County, New Mexico. This report summarizes site conditions, the proposed reclamation plan, ground water modeling and evaluations, and our conclusions and recommendations. Details of data collected during this study, the methodology, and the model documentation are contained in Appendices to this report.

The location of the mine is shown on Plate 1, Location Map. Locations and extent of the major pits and surface facilities are shown with respect to topography, roads and other cultural features on Plate 2, Vicinity Map.

PURPOSE AND SCOPE

As a part of Anaconda's proposed reclamation plan, open-pit mines are to be backfilled to an elevation three feet above the anticipated post reclamation water table recovery elevation. It is, therefore, desired to confidently estimate with a definable margin of error, the maximum probable recovery elevation of the water table in the pits. This will then define the required minimum backfill level. In addition, it is desired to ascertain whether backfilling of protore or waste rock would cause significant deterioration of ground water or surface water quality in the vicinity of the open pits. Such deterioration of water quality could possibly occur due to the physical mixing of the rock materials as a consequence of earthmoving procedures and long-term exposure to the atmosphere, thereby increasing their susceptability to chemical oxidation and leaching. The major objectives of this study are then to define the pertinent site conditions, estimate the positions and rates of ground water inflows into the backfilled pits as a function of time, predict the time required to obtain stable ground water levels within the backfilled areas as well as the elevations reached, estimate the quality of ground water within the backfilled pits as a result of inflows and potential for leaching of protore and waste rock, and estimate the alterations to the quality of ground water and how these might affect the Rio Paguate and Rio Moquino.

In order to accomplish the above purposes and objectives we have compiled existing information and collected additional data as necessary to prepare a numerical computer model for predictive analysis of future conditions in the backfilled pits. The model has been run to determine our best estimate of future water level elevations and water quality and the sensitivity of these solutions to reasonable variations in the input parameters. Our scope of work has included:

1. Site visit and data collection. A site visit was made to study and compile available data from the Jackpile Mine, observe and document current site conditions through written descriptions and photographs and collect bulk surface samples of typical backfill materials. Information collected from Anaconda files has included:

    a. Aerial photographs and topographic and pit progress maps showing the former maximum extent of the North Paguate, South Paguate and Jackpile pits.

    b. Maps showing the horizontal and vertical extent of the P-10 underground mine.

    c. Maps and data showing the locations of stockpiles of waste rock and protore and their planned future placement in the pits.

    d. Information indicating methods of backfilling (truck-dumping) which would have a significant bearing on hydrologic properties.

    e. Selected drill hole and geophysical logs and geologic cross-sections of the pits and vicinity.

    f. Past water level and water quality data for surface and ground waters pertinent to the study.

2. Preliminary data evaluation. We have assembled available hydrogeologic and geochemical properties, reviewed the data and cast these into forms useable in the numerical model. Several preliminary computer runs were made, including calibration runs to premining conditions and predictive runs. This process allowed us to identify the sensitivity of various parameters and the need for additional data. Our preliminary evaluations indicated a need to concentrate our studies around backfill and hydrologic conditions along the Rio Paguate near the North and South Paguate pits.

3. Subsurface exploration. A field exploration program was conducted to acquire additional hydrogeologic, geochemical and ground water quality data. The program included:

   a. Completion of five monitor wells cased to a nominal diameter of six-inches in the backfill in order to obtain water quality samples and ground water levels.

   b. Completion of ten borings cased with two-inch PVC pipe and screen for evaluation of permeability, backfill characteristics and water levels.

   c. Water injection tests in the two-inch cased holes to evaluate permeability.

   d. Measurement of specific capacity of the wells to evaluate the permeability of the backfill.

   e. Injection of slugs of water in the open holes during drilling of the monitor wells to obtain a rough estimates of permeability of the backfill.

   f. Water sampling of ground water from the monitor wells installed during this program and of waters from four ponds and a seep in the open pits.

   g. Field measurement of dissolved oxygen, Eh, pH, conductivity and temperature in the waters listed in Item f above and in selected Anaconda monitoring wells.

   h. Collection of bulk soil and water samples for use in the geochemical testing program.

   i. Surveying of the locations and elevations of the wells and borings installed during this program.

   j. Field observations of major backfill types, thicknesses and characteristics of alluvium and bedrock in the pits and taking additional photographs of pertinent site conditions.

4. Laboratory testing. A laboratory testing program was conducted to physically and geochemically characterize the backfill materials, to measure leachable chemical constituents including uranium and radium-226, and to measure geochemical attenuation. Tests were run on bulk samples obtained during the site visit and subsurface field program. Characterization tests included mineralogic identification by X-ray diffraction, X-ray fluorescence and other means; percent sulfur, sulfate and sulfide; acid potential, neutralization potential, and acid-base potential; calcium carbonate equivalent, cation exchange capacity and extractable cations. Batch leaching/attenuation tests were conducted using native ground water, water presently within the backfill and water from the ponds within the pits.

Physical tests were run to characterize the backfill including, gradation, moisture content, bulk density, specific gravity and laboratory permeability.

5. Modeling and conclusions. We have analyzed and compiled the results of the office data collection, field studies and laboratory testing program, devised model cases and conducted model calculations by runs of the computer program embodying the model. The computer program employed accounts for flow and mass transport as described in the Appendix B to this report.

6. Summary report. This summary report, along with Appendices thereto have been prepared to document the data base, site conditions, methodologies used, test cases, predicted results and conclusions drawn.

SITE CONDITIONS

LOCATION

The Jackpile-Paguate Mine is located just east of the village of Paguate, Cibola (formerly Valencia) County, New Mexico, as shown on Plate 1, Location Map. The site is approximately 7 miles north of Laguna and 40 miles west of Albuquerque.

SURFACE FEATURES

The mine is located in an area of rough and broken terrain ranging in elevation from 5,700 to 7,000 feet. The topographic features are characterized by broad mesas and plateaus interspersed with deep canyons, dry washes and broad valleys. The overall topographic slope is to the southeast and south from the flanks of Mount Taylor, the highest topographic feature in the region.

The principal surface water streams in the vicinity are the Rio Paguate and Rio Moquino which flow nearly year round at the mine. The Rio Moquino joins the Rio Paguate at about the center of the mine area as shown on Plates 1 and 2.

The Jackpile-Paguate Mine is comprised of three major open pits and a major underground mine. These are referred to as the Jackpile pit, North Paguate pit, South Paguate pit and the P-10 underground mine. The locations and maximum extents of the mines are shown on Plates 2 and 3.

GEOLOGY

The mine vicinity is underlain by consolidated Mesozoic strata occasionally cut by late Cenozoic diabase dikes and sills and a thin surficial mantle of alluvium, eolian and colluvial deposits. Descriptions of the strata occurring in the region and their water-bearing characteristics are presented in Table 1. Consolidated sedimentary strata dip gently northwesterly at a slope of one to two degrees. A few very gentle north-trending folds have been imposed on the strata. Several near vertical diabase dikes cut the strata and trend northerly to northwesterly. Faulting is very minor. Excellent surficial geology maps have been published (Moench, 1963a; Moench, 1963b; Schlee and Moench, 1963a; Schlee and Moench, 1963b).

Mining in the open pits has involved three major stratigraphic units: the Brushy Basin Member of the Morrison Formation, the Dakota Sandstone, and the Mancos Shale. The Jackpile Sandstone is a localized sandstone unit which is a part of and is at the top of the Brushy Basin Member. The Jackpile Sandstone is believed to be a channel filling within the Brushy Basin mudstone. In many parts of this area, the Jackpile Sandstone is more than 200 feet thick, but thins and pinches out along a line about six miles northwest of the mine (Anaconda Minerals Company, 1982a). It is completely removed by erosion along the cliffs and slopes southeast and south of the mine. The Mancos and Dakota units are overburden and their stripped materials have been placed around the perimeter of the pits. The Mancos Shale and upper part of the Dakota Sandstone comprise a gradational and interfingering series of black shale and sandstone beds which overlie the relatively resistant basal part of the Dakota Sandstone. Alluvial deposits attaining thicknesses of 80 feet occur adjacent to the stream channels of the Rio Paguate and Rio Moquino.

The Jackpile Sandstone is generally fine- to medium-grained, poorly to moderately well sorted and friable. It is composed predominantly of detrital quartz with minor amounts of feldspar, clay galls, chert and igneous rock fragments. It is cemented with kaolinite clay, silica and calcite. Generally, calcite cement predominates near its base and it becomes relatively finer-grained with more kaolinite cement towards the top of the unit. The

Jackpile Sandstone contains discontinuous beds and lenses of bentonitic mudstone. Below the Jackpile Sandstone, the lithology is more characteristic of the Brushy Basin Member, containing silty, sandy or very clayey mudstone with a few interstratified sandstone beds.

GROUND WATER HYDROLOGY

Several consolidated sandstone units of Mesozoic age and alluvium comprise the principal aquifers in the vicinity. The sandstones, including the Bluff Sandstone, the Westwater Canyon Member, and Jackpile Sandstone Member of the Morrison Formation and sandstones of the Tres Hermanos Sandstone Member of the Mancos Shale generally produce low yields of fair to poor quality (Dinwiddie, 1963). The Dakota Sandstone is not known to yield water to wells in the area. The sandstone aquifers are separated by shale, claystone, mudstone, and discontinuous interbedded sandstone. Alluvium along the Rio Paguate and Rio Moquino is saturated and yields small quantities of good to fair quality water above the mine. Alluvium along the Rio Paguate is not utilized for water supply below the mine. The Jackpile Sandstone is not considered to be a good aquifer; however, it reportedly yields from 8 to 10 gpm of potable water to one well in the area. The Jackpile Sandstone aquifer is of limited extent, thinning and eventually pinching out to the northwest of the mine. It is not present to the southeast and southwest due to erosion.

Ground water flow is generally from the northwest to the southeast. Recharge occurs principally from leakage through overlying shale strata beneath the flanks of Mount Taylor and below the perennial Rio Paguate and Rio Moquino. Discharge is by evapotranspiration at the outcrop and ground water discharge to alluvium in stream channels which cut northwesterly into the outcrop, principally along the Rio Paguate, Rio Moquino and Oak Canyon. Outcrop of the Jackpile Sandstone in promontories to the southeast are dry due to their higher topographic position with respect to the stream channels which are cut to the northwest.

Little pre-mining ground water data is available for the Jackpile Sandstone. Several water level measurements in drill holes reported in a previous study (Hydro-Search, Inc., 1981a) suggests a relatively steep piezometric slope west of the North Paguate pit and lower gradients to the north and east. Estimated pre-mining contours based upon computer modeling have been developed and are discussed in a later section of this report. These indicate ground water discharge to be from outcrop areas such as Oak Canyon and into the alluvium along the Rio Paguate and Rio Moquino as shown on Plate 9B. Pit dewatering, well pumpage, and other activities in the mine area have locally disrupted and modified the ground water flow pattern. Current ground water levels are shown on Plate 11. Except locally near open pits and outcrops, ground water in the Jackpile Sandstone is confined.

Average hydraulic conductivity of the Jackpile Sandstone in the vicinity of the mine is quite variable depending upon the amount of argillaceous materials and degree of cementing of the sandstone. Hydro-Search, Inc., (1981a) tested 7 wells among the 24 sites where wells were drilled into the Jackpile Sandstone (see Table 3). The wells indicated an average hydraulic conductivity of 0.22 ft/day and a range of 0.01 to 0.51 ft/day. The U.S. Geological Survey (1982) performed four pumping tests, two in the Jackpile Sandstone, one in alluvium and one in a sandstone in the lower Brushy Basin Member. Results are summarized on Table 4. Summers (1969) performed one pumping test and 28 bailer tests in the North Windwhip area (near the north end of the Jackpile pit). One pumping test indicated a transmissivity and storage coefficient of 17 ft^2/day and 0.0018, respectively. Values of transmissivity calculated from the bailer tests ranged from 0.5 to 10 ft^2/day and averaged 3 ft^2/day. Available data indicates a significantly higher hydraulic conductivity in the area immediately west of the Rio Moquino than in the area east of the Rio Moquino.

Storage coefficients calculated by Hydro-Search,Inc. (1981a) and U.S. Geological Survey (1982) averaged 2.1×10^{-4} giving an average specific storage of 2.5×10^{-6} ft^{-1}. The aquifer was not fully saturated at most of the well sites and, therefore, the storage coefficients appear to reflect semi-confined conditions within the aquifer itself.

Ground water quality of the Jackpile Sandstone is fair to poor with total dissolved solids generally ranging from about 600 to 2,600 milligrams per liter. Principal constituents are sodium, bicarbonate and sulfate. Sulfate generally ranges from less than 50 to over 600 milligrams per liter and generally averages over 500 milligrams per liter. Ground water quality measured in monitor and water supply wells on the site generally meet New Mexico Environmental Improvement Division ground water standards, except for total dissolved solids and occasionally sulfate.

Detailed information on the ground water hydrology of the site is provided in several publications, including Dames & Moore (1979), Hydro-Search, Inc. (1979; 1981a; 1981c); U.S. Geological Survey (1982) and Anaconda Minerals Company (1982a).

SURFACE WATER HYDROLOGY

The principal surface water streams in the vicinity are the Rio Paguate and the Rio Moquino, which flow nearly year round at the mine. The Rio Moquino joins the Rio Paguate at about the center of the mine area as shown on Plates 1 and 2. Perennial flow in the Rio Paguate has its source in springs issuing from the base of basalt flows on the flanks of Mount Taylor northwest of the mine. Mean daily flow is approximately one cubic foot per second (cfs) and typically flow ranges from one half to three cfs. Five stream surveys on flows through the mine area in the Rio Paguate indicated an average gain in flow of 50 gallons per minute and change from a net loss of 83 gpm to a net gain of 135 gpm. The values for net gain and loss include the effects of gain in the stream flow due to discharge of ground water from the Jackpile Sandstone and loss in the stream flow due to evapotranspiration along the channels (Hydro-Search, Inc., 1981c, p.17). Little data is available on flow in the Rio Moquino. Its perennial flow source is also springs on the flanks of Mount Taylor, but much of its base flow is diverted for irrigation near the village of Moquino.

Alluvium along the stream channels is in direct hydraulic communication with the streams and ground water levels are nearly the same as the stream elevation. The Rio Paguate crosses a portion of backfilled open pit mine near the intersection of the North and South Paguate pits (see Plate 2). The stream does not appear to be in good communication with the backfill as evidenced by the small observed rate of flow into the pits and the deep water levels in backfill adjacent to the stream. The stream channel through this portion of the mine area has been rerouted in a man-made channel in which a clay liner has been placed to reduce seepage to the mine (Herkenhoff and Associated, Inc., 1973). Hydro Search, Inc., (1979) indicated stream losses of 50 gpm across the backfilled portion of the pit. Discharge from a seep in backfill in the North Paguate pit, presumably derived from ground water seepage from the stream, has been observed.

EXCAVATION AND BACKFILL

Excavation of the Jackpile pit began in 1953; mining in the Paguate pits began about 10 years later; and the P-10 underground mine was started in 1974. The maximum extent and depth of the mining has been compiled from detailed pit progress and mining maps. Maximum extent of the mines is shown on Plate 3. Overburden materials consisting of Mancos Shale, Dakota Formation and Jackpile Sandstone were stripped and placed in a series of dumps which surround the pits as shown in detail in the reclamation report (Anaconda Minerals Company, 1982b, Plate 4.1-2). During mining of uranium ore after stripping, waste rock consisting mainly of Jackpile Sandstone was often moved to mined-out portions of the pit. Mineralized sandstone which had too low uranium content for economic use was stockpiled outside the pits. This material is called protore. Much of the backfill currently in the pits, particularly at lower elevations, is Jackpile Sandstone waste rock containing little mineralization. Future reclamation plans call for backfilling with protore piles and dump materials principally of Jackpile Sandstone. Backfill materials which have been and will be placed in the pits are end-dumped from high fills. This causes a natural segregation of material sizes with coarse materials and large blocks near the toe of the fill. The hydraulic conductivity of the resulting backfill is highly variable. Hydro-Search, Inc. (1981a) reported a permeability of 190 ft/day at well M-24 in backfill. Injection and specific capacity tests conducted during our study indicate a range of hydraulic conductivity from 1.2 to greater than 1,000 ft/day.

Laboratory tests of 12 samples of recompacted dump materials, indicative of the silty sand matrix of the backfill, gave an average permeability of 2 ft/day. This latter value would be indicative of the lowest permeability of parts of the backfill other than shale waste.

Present ground water levels in the fill, as shown on Table A-2 of Appendix A, are variable and are governed by pond levels, undulations in the pit bottom elevation and local conditions. Immediately below the channelized Rio Paguate (well F), ground water levels are 32 ft below stream level.

RECLAMATION PLAN

A reclamation plan has been prepared by Anaconda Minerals Company (1982b) which calls for backfilling the pits to an elevation three feet higher than the anticipated ground water recovery level. The source of the backfill material and its location and maximum planned elevation of placement in the pits has been identified (see reclamation plan). The backfill will be topped with one foot of topsoil to promote vegetation and four feet of shaley materials to inhibit access to the Jackpile Sandstone. This overburden and topsoil will help reduce deep infiltration and promote vegetative uptake of runoff. The reclaimed pit areas will, in part, have internal surface drainage.

GROUND WATER FLOW MODELING AND RESULTS

GENERAL

A ground water flow model was prepared in order to estimate pre-mining potentiometric contours, volumetric discharge from the Jackpile Sandstone to alluvium along the Rio Paguate and Rio Moquino, recharge to the Jackpile aquifer, long-term potentiometric contours following reclamation of the mine, and time for recovery of water levels in the backfilled pits. A mathematical model was prepared and run on a digital computer using a computer code named TARGET developed by Dames & Moore. Input parameters for the model were selected based upon field data developed during this and previous studies, geohydrologic principles and assumptions, and through a process of model calibration and verification. The model was then run to predict short-term and long-term water levels in the aquifer by inputting appropriate future material properties and hydrologic conditions. A summary listing of the cases run is given in Table 6. The flow model has been also used in conjunction with evaluation of future ground water quality effects as discussed in a later section of this report.

A brief discussion of pertinent site conditions and reclamation plans upon which the model is based has been previously presented. Additional specific information is contained in the following.

COMPUTER PROGRAM

A computer code named TARGET developed by Dames & Moore was used in this study to solve for steady-state and transient hydrodynamics and chemical transport. The program is capable of predicting flow and chemical transport in both saturated and unsaturated porous media. TARGET utilizes an integrated finite difference formulation for solution of the appropriate equations. The mathematical foundations and detailed development of equations utilized in the program as well as the numerical algorithms used to solve the equations are discussed in the Appendix B to this report.

SELECTION OF PARAMETERS

MODEL EXTENT, BOUNDARIES AND GRID SPACING

The mathematical model used to evaluate flow conditions consists of a two dimensional plan view of the Jackpile Sandstone aquifer and its interconnection with the alluvial aquifer in the mine region. Areal extent of the model is shown on Plates 1 and 4. The model encompasses the Jackpile Sandstone from its erosional removal southeast and southwest of the mine to its pinchout northwest of the mine. The model extends approximately seven and one-half miles to the northeast and to the southwest of the mine. Although the northwest boundary of the model does not represent the true limit of the Jackpile Sandstone it is well beyond significant influence of the hydrologic variations of the Jackpile-Paguate Mine and vicinity. The grid is oriented such that the base of the grid, as shown on Plate 4, trends in the direction of north 49° east (see also Plate 1). Grid spacing is variable and is shown in detail on

Plate 4. The upper (northwest) boundary of the model, the left boundary, and the right boundary all have been set as zero flux (impermeable) boundaries. In order to simulate the outcrop of the Jackpile Sandstone and its contact with alluvium along the Rio Paguate and Rio Moquino, an area of high hydraulic conductivity was placed along the lower portion of the grid and a fixed head was placed along the lower edge of the grid as shown on Plates 7A and 7B. The fixed head along the bottom of the grid was set at elevation 5840 feet, well below the base of the Jackpile Sandstone. A fixed head was also placed at the upper reach of the Rio Paguate alluvium to allow simulation of the interconnection of the Rio Paguate and the Rio Moquino surface streams along the extent of the alluvium. The fixed head was set at elevation 5980 feet in two nodes ([18,22] and [19,22]) to simulate ground water levels in alluvium along the Rio Paguate at its uppermost interconnection with the Jackpile Sandstone. By fixing the heads in these nodes, ground water levels in nodes representing alluvium downgradient closely approximate those encountered in the field. Recharge to the system was simulated by constant flux over a large areal portion of the aquifer as discussed in a later section. This combination of boundary conditions allows simulation of ground water flow from recharge areas on the flanks of Mount Taylor and along the Rio Paguate and Rio Moquino, to outcrop areas along the exposure of the Jackpile Sandstone and its contact with the alluvium.

THICKNESS AND DEPTH OF AQUIFERS

Elevation of the base of the Jackpile Sandstone was input to the model based upon a simplification of structural contour maps provided by Anaconda Minerals Company (1982a). Elevation of the base was approximated based on a uniform strike of north 62° east and a dip of one degree northwest (Plate 5). The thickness of the Jackpile Sandstone was input to the model on a cell-by-cell basis based upon a detailed map showing thickness of the unit at several hundred drill hole sites (Anaconda Minerals Company, 1982a). The thickness contours are shown on Plate 6. The combination of saturated thickness and hydraulic conductivity of the Jackpile Sandstone was used in the model to estimate transmissivity on a cell-by-cell basis.

Elevation of the bottom of the alluvial aquifer and thickness of the aquifer were based upon available field data and were varied on a cell-by-cell basis along the reach of the Rio Paguate and Rio Moquino. Beyond the area of actual interconnection of the alluvial aquifer and the Jackpile Sandstone a zone of high conductivity was used to simulate the ability of the Jackpile Sandstone to freely discharge at the outcrop. Due to the topographically high position of the Jackpile Sandstone along some of the cliffs southeast of the mine, the Jackpile Sandstone is unsaturated both in reality and as modeled.

MATERIAL PROPERTIES

Properties of the aquifer materials, including hydraulic conductivity, specific storage, and specific yield were varied from place to place in the model. Table 7 lists these properties and the values utilized in the model. Plates 7A and 7B show the areal distribution of the properties.

Hydraulic Conductivity

The hydraulic conductivity of the Jackpile Sandstone was based upon values obtained from seven pumping tests reported by Hydro-Search, Inc. (1981a, Table 2), two pumping tests conducted by the U.S. Geological Survey (1982, Table 15), the results of pumping and bailer tests by Summers (1969), injection tests conducted during this study, and notes on yields of the M-series wells (Hydro-Search, Inc., 1981). The pumping test data indicate variable hydraulic conductivity which generally is greater in the vicinity of the mine and decreases to the west of the South Paguate pit and to the east of the Rio Moquino. Steepened ground water level contours to the west of the mine also suggest a decreasing transmissivity to the west.

In the pre-mining simulation (Case 1), a hydraulic conductivity of 0.25 ft/day was utilized in the vicinity of the North Paguate pit and to the north and south of that pit. A hydraulic conductivity of 0.1 ft/day was utilized to the west of this area. A value of 0.05 ft/day was used east of the Rio Moquino as shown on Plates 7A and 7B. These values lie within the range of reported test values and were found suitable in the calibration and verification process.

A hydraulic conductivity of 22 ft/day was utilized for alluvial materials based upon the pumping test data given in U.S. Geological Survey (1982).

In evaluating post reclamation ground water flow, a hydraulic conductivity for pit backfill of 190 ft/day was utilized for the base case. To evaluate the sensitivity of the computed water levels to the hydraulic conductivity of the backfill, values of 2 ft/day and 20 ft/day were utilized in the sensitivity analyses.

Storativity and Porosity

The storage coefficient for confined conditions in the Jackpile Sandstone was modeled based upon a specific storage of 2.5×10^{-6} ft^{-1} and the entire thickness of the aquifer. The specific storage value is based upon the pumping test data given in Tables 3 and 4. Little data is available on specific yield of the Jackpile Sandstone. For unconfined conditions a storage coefficient (specific yield) of 0.20 was used in the model based upon data for materials with similar gradations as given in Johnson (1967). Total porosity of the Jackpile Sandstone is estimated at about 28 percent based upon an in situ density of 120 pounds per cubic foot.

Total porosity of backfill is estimated at 45 percent based upon representative recompacted samples tested in our laboratory. The initial volumetric moisture content was measured at approximately 15 percent. Therefore, an unconfined storage coefficient (specific yield) of 30 percent was utilized in the model. The backfill is never under confined conditions and, therefore, a confined storage coefficient is not required.

An unconfined storage coefficient (specific yield) of 30 percent and a total porosity of 45 percent were utilized in the model based upon data for similar materials. Virtually no changes occur in water levels in alluvium. Therefore, the model is insensitive to the values chosen for storativity of the alluvium. Storativity is only utilized in the model in transient cases (cases 2 and 4).

RECHARGE

Recharge to the Jackpile Sandstone aquifer was estimated in a two-step process: first, a rough estimate of the recharge rate was made based on estimated physical properties; and second, recharge was adjusted to a final value during the calibration process of the modeling. Recharge to the Jackpile Sandstone occurs by leakage through overlying strata. Based on review of geologic maps, recharge areas were identified as areas of alluvium and colluvium lying adjacent to perennial streams, high plateau areas covered with basalt flows (principally west and northwest of the mine), and colluvium covered slopes on the flanks of higher mesas. It is assumed that negligible recharge occurs over areas where exposed materials are of low permeability (such as Mancos Shale) and there is a lack of vegetation. In these areas, precipitation would be expected to run off or evaporate before significant infiltration can occur. Based upon approximate or assumed hydraulic gradients and permeabilities of overlying materials at typical locations, recharge rates were input to the model. These rates were then adjusted to obtain an appropriate fit to the ground water levels during the calibration and verification.

Recharge areas selected for the model are shown on Plate 8. Two rates were utilized. A recharge rate of 0.24 inch per year was used for alluvial areas adjacent to the perennial Rio Paguate and the high, basalt covered plateau northwest of the mine from which springs issue; a lower recharge rate of 0.12 inch/yr was used for the colluvium covered slopes west and northwest of the mine and along the northern Rio Moquino. The total recharge rate to the model is 12,700 ft^3/day (66 gpm).

CALIBRATION TO PRE-MINING CONDITIONS (CASE 1)

The areal distribution of pre-mining ground water levels, flow directions, and flow rates were estimated utilizing the input parameters discussed previously and listed on Table 7. Ground water contours as calculated and contoured by the computer are shown on Plates 9A and 9B. The match to the few pre-mining ground water levels and the general flow pattern depicted are reasonable and adequate. It is not possible to match every measured water level exactly without using complex material property distributions which cannot be justified on the basis of available hydrogeologic data. Where observed water levels do not match calculated values exactly, calculated values are greater. This makes the model conservative.

Flow is shown to occur from the west and northwest with discharge occurring into Oak Canyon, and to alluvium along the Rio Moquino. A relatively small amount occurs directly to alluvium along the Rio Paguate. Flow to the upper Rio Paguate is small because water levels in the alluvium are relatively high due to the elevation of the stream. East of the Rio Moquino flow is from the north and northeast.

The model calculates a discharge of 8 gpm into the upper reaches of Oak Canyon along an outcrop distance of about one mile. This discharge would be consumed by evapotranspiration. Underflow in alluvium just below the confluence of the Rio Moquino and Rio Paguate is calculated at 100 gpm. Of this, 77 gpm is generated by the Rio Paguate surface stream (by means of the constant head nodes), leaving a net 23 gpm being discharged from the Jackpile Sandstone upstream from the confluence. Thirteen gpm of the 23 gpm is derived by flow from the Jackpile Sandstone to alluvium along the Rio Moquino.

VERIFICATION TO END OF MINING CONDITIONS (CASE 2)

The areal distribution of ground water levels, flow directions and flow rates were calculated for the end of mining in order to compare calculated water levels with levels recently observed in monitor wells at the site. Since an adequate match of calculated and observed water levels was achieved, the model was considered verified.

All input parameters to the model were the same as those used for the calibration (Case 1) except that constant head conditions were specified in the cells representing the open pits and underground mine at appropriate times and at appropriate elevations to simulate progressive mining. It was assumed that mining excavation progressed at linear rates during the mining period of each pit. A constant head condition was not specified unless the computed base of the excavation dropped below the computed ground water level.

The simulated mining schedule and approximate rate of mining used in the model is shown graphically on Plate 10. As shown, excavations in the various pits begin at different times. Mining in the Jackpile pit is modeled to occur over two time periods. Mining at Sohio's L-Bar underground mine, located 1.9 miles north of the Jackpile pit, began in late 1976 and was included in the model by placing a constant head in node [35,26].

Case 2 is a transient situation run with initial ground water levels being taken from the pre-mining steady-state condition computed in Case 1. Computed water levels after 29 years of mining and one year of recovery are shown along with observed levels on Plate 11. The match to observed water levels and the general flow pattern are reasonable and indicate an adequate model. Localized conditions and the relationship of the location of each well to the discretized model must be considered. The water level in monitor well M-21 lies near the contact of sandstone which overlies sandy clay, siltstone and minor sandstone, all within the nominal Jackpile Sandstone unit. This condition may account for the anomolously high water level measured in M-21. Water levels at M-11 are at seemingly anomalously low levels for the hydrogeologic location and in comparison with surrounding water levels. However, the vicinity of M-11 may be affected by the pumping of Jackpile Water Well #4 which was constructed with a gravel pack which extends from the casing perforations upward across the entire section of Jackpile Sandstone. These possible effects were not incorporated into the model.

LONG-TERM RECOVERY WATER LEVELS

BASE CASE (CASE 3)

Long-term, steady-state elevations to which ground water levels will recover in the backfilled pits have been calculated using the same model parameters used in the pre-mining situation (Case 1) except that backfilled pits and the P-10 underground mine area were assigned a hydraulic conductivity of 190 ft/day. The time required for recovery of water levels after reclamation is estimated at greater than 300 years as discussed in detail in a subsequent section. Evaluation of long-term, steady-state ground water levels under somewhat modified conditions is given in the following section entitled SENSITIVITY ANALYSES. Water levels calculated for representative nodes in each pit for the base case and the sensitivity analyses are given in Table 8. Long-term, steady-state water levels for Case 3 are shown on Plates 12A and 12B, and are discussed for each pit in the following.

Jackpile Pit

Water levels in the Jackpile pit are predicted to stabilize at elevation 5929 ft, which is up to about 15 feet lower than predicted pre-mining levels. Steady-state flow through the backfill is calculated at 290 ft^3/day (1.5 gpm). Predicted water levels are a minimum of 9 feet below the planned pit backfill level.

South Paguate Pit

Water levels are predicted to stabilize at 5982 to 5985 ft or 11 to 18 ft below the planned backfill level. Most flow is shown to occur from the pit to the southeast, eventually discharging along the outcrop area of Oak Canyon. A small amount would discharge to alluvium of the Rio Paguate. The backfilled pit is shown to strongly change flow directions and ground water contours only in the immediate vicinity of the pit. Flow, at a rate of 1.3 gpm, is calculated to flow directly to stream alluvium through backfill along the Rio Paguate. Ground water flow to the alluvium from the southern part of the South Paguate pit is restricted by the relatively shallow depth of excavation (elevation 5980 ft) in the northern part of the pit (see Plate 3). Total flow out of the pit is calculated at 2100 ft^3/day (11 gpm).

North Paguate Pit

Under the given model parameters, ground water levels in the North Paguate pit are shown to stabilize at elevation 5972 to 5979 ft, or some 15 ft higher than planned pit backfill levels. Inflow directly from alluvium is calculated at 6200 ft^3/day (32 gpm). The model assumptions are very conservative and, therefore, must be evaluated further. A constant head node [19,22] of 5980 ft in alluvium is in direct hydraulic connection with the pit backfill. Flow out of the pit as modeled must occur through Jackpile Sandstone which possesses a much lower transmissivity than either the alluvium or pit backfill.

Field data, however, show that alluvium extends to depths of 5963 ft elevation on the presently exposed south wall of the North Paguate pit and to 5914 ft elevation at Boring HD near the southeast corner of the pit. Adjacent stream levels range from 5975 to 5950 ft. No discharge of ground water from alluvium to the pit was observed. In the western part of the pit, a large fill containing abundant shale presently exists which would be expected to partially block ground water flow. Contradicting this hypothesis, however, is the fact that a spring was observed to flow at about 100 gpm from the base of the fill. The rechannelized Rio Paguate is clay-lined in the portion of the stream overlying backfill. This serves to limit the maximum rate of flow which occurs from the stream.

Modeling of flow with direct hydraulic connection between the southeastern part of the pit and stream alluvium, indicates high rates of flow, through the pit backfill with water levels rising above ground surface at the contact of the high permeability backfill and the alluvium. This would form a surface seep area. In reality, such high flow rates out of the stream and into alluvium would not likely occur since the channel is lined. This clay-lined condition cannot be directly modeled. Based upon visual observation, current flow is approximately 100 gpm into the pit through the backfill in the western part of the pit. Hydro-Search, Inc. (1979) reported stream losses of 50 gpm over the backfill based upon stream measurements.

Based on the above we would expect equilibrium ground water levels to be below the elevations predicted by Case 3. However, to positively control levels in the North Paguate pit, we recommend that select low permeability backfill be placed along a north-south line in the western part of the pit in order to form an internal cut-off through the fill. Details of this recommendation are given in Case 3.5 and the subsequent section entitled <u>CONCLUSIONS AND RECOMMENDATIONS</u>. Hand calculation of the flow rate through the dam have

Model calculations show that recovered ground water levels in the South Paguate pit are affected to a small extent, about 1 foot, from levels computed for the base case (see Table 8). Levels in the Jackpile pit are the most sensitive and are raised six feet. Levels in the North Paguate pit are virtually unaffected. Plate 15 shows ground water contours computed for this case.

Sensitivity to Infiltration into Backfill - (Case 3.4)

This case is similar to Case 3.3 except infiltration over backfill areas of each pit was set at a rate of 0.12 inches per year. Model calculations show that long-term water levels are raised by approximately 2 feet in the South Paguate pit, by 16 feet in the Jackpile pit, and to a negligible extent in the North Paguate pit (see Table 8 and Plate 16).

NORTH PAGUATE PIT WITH INTERNAL CUT-OFF (CASE 3.5)

A model run was made to evaluate water table elevations which could be achieved in the North Paguate pit with placement of an impervious cut-off through the pit or "backfill dam." Such a cut-off was previously discussed under Case 3 on page 19 and is further outlined under the section DISCUSSIONS AND RECOMMENDATIONS. This was done by running the model with the same parameters as for Case 3 except that a hydraulic conductivity of 0.02 ft/day was assigned to node [22,22]. This conductivity is 7 times greater than the estimated actual backfill conductivity; however, the size of the model block compared to the assumed width of the cut-off compensates for this difference, and the model accurately simulates the effect of the assumed cut-off.

Model calculations indicate that water levels in fill west (upgradient) of the cut-off are 5,979 feet, nearly equal to stream level, while water levels in the pit downgradient from the cut-off are at elevation 5,946 to 5,948 feet, some seven feet below the planned backfill level. Flow through cell [22,22] is calculated at 1 gpm. Total flow out of the backfill is calculated to be 20 gpm.

EXISTING WATER QUALITY IN BACKFILL AND PONDS

Measurements of ground water quality in the backfill have been made at three newly installed wells: Well B in the South Paguate pit, Well C in the North Paguate pit, and Well D in the Jackpile pit. Water quality of ponds in these pits has also been measured. Well and pond locations are shown on Plate 3. Field measurements and laboratory analyses are summarized in Appendix A.

In the backfill, total dissolved solids (TDS) ranged from 3788 to 8173 mg/l while sulfate ranged from 2010 to 5560 mg/l. Field pH ranged from 6.1 to 7.7 units. Oxidizing conditions prevail with dissolved oxygen (DO) ranging from 0.37 to 0.90 mg/l and Eh ranging from -106 to +116 millivolts (mv). These oxygen levels are a small fraction of the oxygen levels which would occur under fully oxygenated conditions such as in a surface pond.

Uranium ranged from 0.005 to 1.95 mg/l while radium-226 ranged from 5.5 to 11.8 picocurie per liter (pCi/l). Except for TDS and sulfates, all analyses meet New Mexico Environmental Improvement Division (EID) ground water quality standards. This existing water quality is probably representative of the worst condition which will occur since the ratio of water to potentially contacted backfill is at its greatest. Also, with continued inflow of ground water reducing condition will eventually be reestablished.

Waters in the ponds and the seeps had lower TDS, ranging from 896 to 3256 mg/l, and lower sulfate, ranging from 540 to 2270 mg/l. Field pH ranged from 6.9 to 9.6 units. Uranium ranged from 0.85 to 5.96 mg/l and radium-226 ranged from 8.1 to 65 pCi/l. Radium-226 in the seep at the west end of the North Paguate pit; and radium-226 and uranium in the pond in the North Paguate pit exceed EID ground water standards. Otherwise, except for TDS and sulfate, pond waters meet EID ground water standards. It should be noted that EID standards are not necessarily applicable in a legal sense, but are used herein for the purpose of comparison to use criteria.

for these samples has been measured and is presented on Table A-15 of Appendix A. Cation exchange capacity of samples of Jackpile Sandstone origin range from 4.9 to 17.9 milliequivalents per 100 grams (meq/100g). Calcium is the predominant exchangeable cation. Comparison of the CEC and the mineralogic data shows a direct relationship between the CEC and the smectitic mineral concentrations. While kaolinite, illite and chloride provide some exchange capacity, their effect is greatly subordinate to the smectitic minerals.

The oxidation of pyrite (FeS) will affect the ground water composition by decreasing the pH and increasing the sulfate concentrations. However, the concentrations of pyrite are low in the Jackpile Sandstone and the concentrations found in the Mancos Shale are typical of other marine shales. Site materials also contain abundant material to neutralize acid which might be generated by the oxidation of pyrite. Table A-16 of Appendix A gives acid forming potential, neutralization potential and acid-base potential as well as sulfur content and form for representative samples. Materials derived from the Jackpile Sandstone (protore, Jackpile Sandstone mining waste and backfill) have capacity to neutralize in excess of the acid forming potential. Materials derived from dark shales (Mancos and Dakota Shale) generally have a net acid forming potential. Since planned backfill will be predominantly derived from the Jackpile Sandstone, acidic conditions in the backfill should not occur. Materials which will be placed in the North Paguate and South Paguate pits are derived mainly from the Jackpile Sandstone. Lab test data (Appendix A) shows this material has a large neutralization potential. Mixed materials as well as materials derived from the Jackpile Sandstone are to be placed in the Jackpile pit. Calculation of the acid-base potential for all backfill materials to be placed in the pit indicates that neutralization potential exceeds acid potential giving a net acid-base potential of 0.1 tons/1,000 tons $CaCO_3$ equivalent.

BATCH EQUILIBRIUM TESTS

A series of batch equilibrium tests, consisting of mixing typical backfill materials Jackpile Sandstone and alluvium with waters from the site, were conducted in order to evaluate constituents which may leach out of the soil and to evaluate soil adsorption characteristics. Details of the methodology, data and results of these experiments are given in Appendix A.

In these tests, waters taken from M-6, Well B, and Pond Z (northern Jackpile pit), were contacted with typical backfill materials in a 1:1 weight ratio. Analysis of the waters before and after contact were made to evaluate changes in water chemistry. Water from well M-6 had the best water quality; that is the lowest TDS, sulfate, radium-226 and uranium. Water from Well B had the highest TDS and sulfate, but uranium and radium were less than that of the Pond Z sample. Results of the contacting of these waters with various soils are complicated.

TDS increased an average of five times with contact between soils and M-6 water. Materials classified as "mixed dumps" and the undisturbed Jackpile Sandstone sample had the greatest TDS and sulfate increases; the alluvium sample had the smallest increase (about a factor of three for TDS and sulfate). Calcium was the principal cation to increase, but its increase was generally greatest for mixed dump materials. Sodium increased for the protore and Jackpile mine waste samples, but decreased for mixed dump, undisturbed Jackpile Sandstone, and alluvium samples. Radium-226 was leached from every sample except alluvium, but exceeded EID ground water standards for only two of the three protore samples. Uranium was leached from every sample and exceeded EID standards for several samples including two protore, the Jackpile mine waste and the undisturbed Jackpile Sandstone samples.

Samples contacted with the poorest quality water, from well B, showed little change in TDS and sulfate. Radium-226 increased the most with contact with the mixed dump sample. A small increase in radium was measured for the Jackpile mine waste sample. Radium decreased for the undisturbed Jackpile Sandstone and alluvial samples. Uranium increased with contact with all soils.

Samples contacted with water from Pond Z, which contained intermediate levels of sulfate and TDS, but the highest levels of radium and uranium, showed about a 30 percent increase in TDS and about a 20 percent increase in sulfate. Calcium increased significantly while there was little change in sodium. Radium decreased with all soils except one mixed dump sample. Uranium decreased with all samples except the undisturbed Jackpile Sandstone sample.

Overall, the tests indicate that higher TDS and sulfate would be expected from backfill containing shales (mixed dumps). These materials generally contain more pyrite and would also pose greater acid-forming potential than materials containing primarily sandstone. Uranium and radium was leached from all samples where the initial water contained very low concentrations. Protore showed the greatest leaching of radium, although mixed dump materials also showed a high degree of leaching. Uranium was leached from all samples where the initial water concentration was very low. Greater concentrations of uranium were leached from the protore, Jackpile Sandstone and Jackpile Sandstone mining waste samples than from mixed dump and alluvium samples. The degree of leaching which occurred during the test is expected to be much greater than that which would occur in the actual backfill due to the much more highly oxidizing environment in the lab tests.

Distribution coefficients (Kd) can be calculated for radium-226 with the data from Tables A-21B and A-21C as listed on Table A-22. Relatively small values ranging from 0.2 to 11.5 milliliters per gram (ml/g) were obtained for Jackpile Sandstone and alluvium. Distribution coefficients for uranium, calculated from Table A-21C, ranged from 1.5 to 9.8 ml/g. The relatively low values obtained from these tests probably are due to the relatively high radium and uranium concentrations in all the backfill, the undisturbed Jackpile Sandstone and alluvium samples.

Batch equilibrium tests were also conducted by Hydro-Search, Inc. (1981c). In these experiments, water taken from the P-10 underground mine was contacted at a 1:1 ratio with samples of Jackpile Sandstone, protore, Dakota sandstone, and Dakota shale. The tests showed increases in TDS due principally to increases in sodium and sulfate. TDS increased from 557 mg/l in the P-10 water to 880 mg/l in the Jackpile Sandstone and to 1,256 mg/l in the Dakota shale sample. Sulfate increased from 130 mg/l to 280 mg/l in the Jackpile Sandstone and to 625 mg/l in the Dakota shale. pH of the mixtures ranged from 7.6 to 8.3 units. Radium-226 had a relatively high level in the P-10 water of 26 pCi/l. After contact with the soil, radium-226 dropped to 1.1 pCi/l or less except in the protore sample in which it increased to 52 pCi/l. Uranium, initially at a level of 0.22 mg/l in the P-10 water, dropped in all samples except the protore in which it increased to 22 mg/l. Other than radium and uranium in the protore sample, sulfate in the Dakota shale sample, and TDS in the protore, Dakota sandstone and Dakota shale samples, constituents in the mixtures met EID ground water standards.

Distribution coefficients (Kd) for radium-226 can be calculated from the Hydro-Search data. These are 22 ml/g for the Dakota shale, 67 ml/g for the Dakota Sandstone, and 216 ml/g for the Jackpile Sandstone sample. Kds calculated for uranium are 0.05 ml/g for the Dakota Sandstone sample, 6 ml/g for the Dakota Shale and greater than 22 ml/g for the Jackpile Sandstone. Radium-226 and uranium were leached from the protore sample.

Distribution coefficients reported in the literature are much higher than those calculated from the batch test results. Schneider and Platt (1974, pp. 3.53-3.54) give a distribution coefficient of 100 ml/g for radium and 3,000 ml/g for uranium for typical western desert soil consisting of "sand of moderate cation-exchange capacity (about 5 milliequivalents per 100 grams) to sandy loam containing about 1 milligram of free $CaCO_3$ per gram of soil." The geochemistry of radium and uranium are discussed in U.S. EPA (1978). This paper cites numerous test results all indicating distribution coefficients for radium greater than 200 ml/g and indicates a direct correlation of cation exchange capacity with adsorption. While adsorption is a good model for radium migration, the mobility of uranium is controlled by many factors including oxidation-reduction conditions and pH. Mobility of uranium increases under oxidizing environments and uranyl ions form many complexes. Uranium is highly adsorbed by organic materials and clay especially in the slightly acidic range. Distribution coefficients for uranium ranging from 16 to 270 ml/g for clayey soils were reported. Pure quartz was indicated to be inert (Kd=0).

The distribution coefficients (Kd) calculated from laboratory data in Appendix A are lower than reported literature values. This is believed to result from the relatively high radium concentrations in solid materials in the pit vicinity. Since adsorption is an equilibrium process, and since concentrations in the liquid fraction are relatively low, Kd values for these interactions would be expected to be lower. At greater distances from the ore body, such as southeast of the South Paguate pit, distribution coefficient indicative of those reported in the literature (100 ml/g) would be expected. Likewise, uranium would be expected to have a higher Kd, likely exceeding 10 ml/g.

SUMMARY

Based upon available water quality data from monitor wells at the site, backfill geochemical characteristics, batch equilibrium tests and literature information, total dissolved solids in the backfill are estimated to reach 5,000 to 10,000 mg/l, with sulfate, sodium and calcium predominating. Bicarbonate is expected to be about the same as background levels in the aquifer. Sulfates are expected to range from 3,000 to 6,000 mg/l. The highest concentrations are expected to occur initially as the pit fills with ground water. Subsequently, additional leaching is expected to decrease as dissolved oxygen is depleted and equilibrium conditions are established. Backfill containing abundant shales would contribute more dissolved solids and sulfate, and would have higher acid-forming potential than materials predominantly composed of sandstone. Protore has a higher potential for contributing radium and uranium. Water quality analyses from monitor wells in the backfill show radium-226 and uranium to be well below EID standards. Laboratory batch tests probably overstate uranium concentrations since ground water in the backfill should be under much less oxidizing condition. It appears there is potential for uranium and radium-226 to locally exceed 5 mg/l and 30 pCi/l, respectively, in areas of predominantly protore backfill. Heavy metals, selenium, arsenic and other trace constituents are not expected to exceed EID standards in the backfill. Radium transport would be controlled by ion exchange mechanisms while uranium transport would be controlled by oxidation-reduction reactions and secondarily by ion exchange.

CONTAMINANT MIGRATION

SEEPAGE MOVEMENT

Ground water flow conditions have been described previously. Significant flow out from the backfill will not occur until ground water levels recover to near steady-state conditions. The time to reach a condition of outflow from the pits is estimated at 30, 150, and 300 years for the North Paguate, South Paguate, and Jackpile pits, respectively. The total flow rates from the pits are small, estimated at 20, 11, and 1.5 gpm for the North Paguate, South Paguate, and Jackpile pits, respectively.

The predicted direction of ground water flow is perpendicular to potentiometric contours shown on Plate 12 through 17. Flow from the North Paguate pit will be east to southeast eventually discharging to alluvium. Ground water from the Jackpile pit will move in a southerly to southwesterly direction eventually discharging to alluvium. Flow from the South Paguate pit will be principally southeasterly and easterly, eventually discharging at the outcrop where it will be consumed by evapotranspiration. A small part of the 11 gpm flow from the South Paguate pit will move toward the Rio Paguate, to discharge to alluvium.

CONSTITUENT CONCENTRATIONS

Transport of dissolved constituents has been modeled using the numerical model with the same conditions as discused for Case 3.5. This situation is a steady-state flow condition representative of post-mining conditions (with a cut-off through fill in the North Paguate pit). Significant outflow from the backfilled pits will not occur until ground water levels recover to near steady-state conditions. Individual pits reach steady-state at different times; therefore, the simulation of transport is a close approximation for individual pits with times measured from the time each pit reaches steady-state. A longitudinal dispersivity and a transverse dispersivity of 20 feet and 5 feet, respectively, were utilized. No vertical mixing was assumed; therefore, concentrations represent maximum values lateral to the pit. These values are conservative based upon results of field measurements of dispersion reported in the literature.

The model simulations are based upon assuming that one pore volume of water within the pit boundaries attains full concentration (normalized to a value of 1.0) upon filling with ground water and that ground water subsequently flowing into the backfill causes no further leaching.

<u>Species Undergoing No Geochemical Interactions (K_d=0)</u>

Predicted normalized concentration contours for species undergoing no chemical interactions (K_d=0) with the aquifer are shown for 20, 60, 100, 180, and 260 years after release on Plates 18A, 18B, 18C, 18D, and 18E, respectively. Conservatively, total dissolved solids and sulfate concentrations can be viewed as undergoing negligible chemical interactions. As shown on Plate 18E, the model predicts that 260 years after filling with ground water, the 0.3 normalized isoconcentration contour (0.3 isocon) should lie some 2,000 feet east and south of the South Paguate pit. Since a minimum of 150 years will be required for the pit to fill with water, the condition depicted would be predicted to occur 310 years after reclamation. The 0.3 isocon represents an increase in concentration of 30 percent of the amount that the initial concentration in the pit is above background. Expressed mathematically, the concentration in the aquifer along an isocon is:

$$C_a = C_b + I\ (C_m - C_b)$$

Where:

C_a = actual concentration in aquifer
C_m = maximum initial concentration in pit
C_b = background concentration
I = isocon value, also referred to as the ratio C/Co

where $C = C_a - C_b$ and $C_o = C_m = C_b$

Considering sulfate for example, with an initial maximum concentration in the pit backfill of 5,000 mg/l and a background concentration of 700 mg/l, the concentration predicted along the 0.3 isocon is 1,990 mg/l.

Concentrations predicted in alluvium do not exceed a normalized concentration of 0.10 because of simple mixing at the relatively low discharge rates from the pits and the much higher discharge rates through the alluvium. A worse-case estimate of the potential effect on surface water can be made by assuming that the steady-state flow rate from the pits (23 gpm) is discharged to the Rio Paguate at the maximum concentration in the pits. The incremental sulfate concentration increase for the average stream flow (1 cfs) is calculated at 190 mg/l, using an influent sulfate concentration of 5,000 mg/l and a stream background concentration of 1,000 mg/l (Ford Crossing).

Species Which Undergo Geochemical Retardation

Prediction of the effects of geochemical retardation upon migration can also be made by reference to Plates 18A through 18E. In this particular case, because the constituents are a single one-time source and because the effective porosities of the site materials are relatively uniform, the plots generated for no retardation ($K_d=0$) are applicable to conditions with the distribution coefficient (K_d) greater than zero at a different (greater) time. The relationship is expressed:

$$t = (1 + B[\frac{1-\eta}{\eta}]K_d)t_o$$

Where:

- t = applicable time
- t_o = time for condition of K_d equal to zero
- B = bulk density
- η = effective porosity
- K_d = distribution coefficient

Retardation by ion exchange reactions is an important attenuation mechanism for many trace metals including radium and uranium. Distribution coefficients for radium and uranium have been discussed previously. Other trace constituents of potential concern should not exceed EID ground water standards in the backfill.

The effects of chemical retardation are large. Transport velocity for K_d equal to 1 ml/g is less than 1/5 that for unattenuated species and is less than 1/45 that for unattenuated species for K_d equal to 10 mg/l typical of uranium. For K_d equal to 100 ml/g, typical of radium, the decrease in velocity would be 450 fold.

Thus, the iscon distribution shown on Plate 18E would be applicable to 12,000 years into the future for uranium and 110,000 years into the future for radium. The 0.3 iscon for radium would represent a concentration of 23 pCi/l for the worst case assumptions (Cm = 66 pCi/l, Cb = 5 pCi/l). The 0.3 iscon for uranium would represent a concentration of 9 mg/l for worst case assumptions (Cm = 30 mg/l, Cb = 0.6 mg/l). It should be emphasized that these are worst case estimates. Field measurements indicate that maximum concentrations in the backfill of these constituents would be two to five times less than those assumed above. A worst case analysis of the potential effect upon surface water quality indicates a contribution of less than 2 pCi/l of radium-226 and less than 1 mg/l of uranium.

CONCLUSIONS AND RECOMMENDATIONS

Our evaluations indicate that planned backfill levels as shown in the reclamation report (Anaconda, 1982b) are a minimum of nine feet higher than the long-term steady-state ground water levels as predicted for Case 3 except in the North Paguate pit. Estimated long-term steady-state recovered water levels in the pits are summarized on Table 8.

In order to reduce backfill requirements and control ground water levels in the North Paguate pit, we recommend the placement of select materials to form an internal cut-off within the fill. This alternative would control water levels east of the cut-off to levels which are a minimum of seven feet below the planned backfill level. West of the cut-off, backfill should be placed to a minimum elevation of 5983 ft. It is recommended that the internal cut-off be located in the pit at the approximate location shown on Plate 3.

Prior to placement of fill in the cut-off, ponded water should be removed and the ground surface should be cleared of loose materials. The cut-off should be constructed of select materials and placed in lifts so as to achieve a hydraulic conductivity of 1 ft/year. A minimum width of 100 ft is recommended. The cut-off should extend across the full north-south width of the pit and should extend upward to elevation 5980 ft. The cut-off could feasibly be constructed with select available dump material containing a high percentage of silt and clay. An abundant amount of such material is available. With careful selection of materials and adequate moisture conditioning, the recommended hydraulic conductivity of one ft/year should be achievable with materials placed in lifts on the order of one foot in loose thickness and compacted with the action of earthmoving equipment.

The time for recovery of water table levels to essentially steady-state conditions is estimated at 30, 150, and 300 years for the North Paguate, South Paguate, and Jackpile pits, respectively.

Sensitivity analyses were performed to evaluate the effect of lower backfill permeability and the effect of local recharge on steady-state water levels. The results of these evaluations are presented on Table 8 and indicate that recovery water levels are not highly sensitive to reasonable ranges of backfill permeability or potential infiltration.

Field measurements and laboratory data indicate that the water quality of ground water which fills the pits will be significantly poorer than background concentrations in the Jackpile Sandstone. Total dissolved solids in the backfill are estimated to reach 5,000 to 10,000 mg/l with sulfate, sodium, and calcium predominating. Sulfate is estimated to reach 3,000 to 6,000 mg/l. Uranium and radium-226 may locally exceed 5 mg/l and 30 pCi/l, respectively, in the backfill. Heavy metals, selenium, arsenic and other trace constituents are not expected to exceed EID standards in the backfill. The highest concentrations are expected to occur initially as the pit fills with ground water. Subsequently, additional leaching is expected to rapidly decrease as dissolved oxygen is depleted. The pH of ground water is not expected to decrease below 6.0 units. Backfill containing abundant shales will contribute more dissolved solids and sulfate and would have a greater acid forming potential than sandstones. Protore has a higher potential for contributing radium and uranium.

Ground water flow from the North Paguate pit will be east to southeast eventually discharging to alluvium. The steady-state flow rate from the North Paguate pit with the recommended internal cut-off is estimated at 20 gpm. Ground water from the Jackpile pit will move in a southerly to southwesterly direction at an estimated rate of 1.5 gpm, eventually discharging to alluvium. Flow from the South Paguate pit will be principally southeasterly to easterly at a rate of about 10 gpm, eventually discharging at the outcrop where it would be consumed by evapotranspiration. A small amount, estimated at 1.3 gpm, will move from the South Paguate pit toward the Rio Paguate, to discharge to alluvium.

Conservative evaluations of the potential water quality changes in the Jackpile Sandstone have been made. These are shown by a series of isoconcentration contours on Plates 18A through 18E and are discussed on pages 33 through 36. The evaluations show slow, gradual movement and dispersion in the direction of ground water flow of species that undergo negligible geochemical interactions. Constituent concentrations diminish most rapidly in the North Paguate pit due to higher flow rates to alluvium, and diminish least rapidly in the Jackpile pit due to the very small discharge rates. Movement of species which undergo geochemical retardation would be much slower; for example, for a constituent with a distribution coefficient of 100 ml/g, typical of radium, movement would be 450 times slower than for unretarded species. The potentially affected area of Jackpile Sandstone is limited to the immediate vicinity of the pits and the area southeast of the South Paguate pit. No ground water development has occurred in this area historically and none would be expected in the foreseeable future due to the poor aquifer characteristics of the Jackpile Sandstone. Under worst case assumptions, small increases in dissolved solids concentrations, on the order of 190 mg/l for sulfate less than 2 pCi/l for radium-226 and 1 mg/l for uranium, could occur in the Rio Paguate. Thus, while some increase in dissolved solids concentrations may unavoidably occur, these should have negligible impact upon viable ground or surface water resources.

REFERENCES

Anaconda Minerals Company, 1982a, Miscellaneous unpublished files and maps: Anaconda Minerals Company, Grants, N.M.

Anaconda Minerals Company, 1982b, Revised Reclamation Plan, Jackpile-Paguate Uranium Mine, Anaconda Minerals Company, New Mexico Operations: Report dated March, 1982.

Dames & Moore, 1979, Mining and Reclamation Plan, The Anaconda Company's Jackpile-Paguate Uranium Mine, Valencia County, N.M.: Consultant Report dated December, 1976; revised March, 1979.

Dinwiddie G. A., 1963, Ground Water in the Vicinity of the Jackpile and Paguate Mines; in Geology and Technology of the Grants Uranium Region: N.M. Bureau of Mines and Mineral Resources, Memoir 15, P.217-218.

Haan, Charles T., 1977, Statistical Methods in Hydrology: The Iowa State University Press, 378 Pg.

Herkenhoff And Associates, Inc., 1973, Engineers Report, Diversion Channel at Jackpile Mine, Paguate, N.M., For the Anaconda Company: Consultant Report dated June 1973.

Hydro-Search, Inc., 1979, Hydrogeologic Relationships, Rabbit Ear and P-10 Holding Ponds, Jackpile-Paguate Mine, Valencia County, N.M: Consultant Report dated June 15, 1979.

Hydro-Search, Inc., 1981a, Ground Water Hydrology of the Jackpile-Paguate Mine, N.M.: Consultant Report dated February 26, 1981.

Hydro-Search, Inc., 1981b, Data on M-Series Wells, Jackpile-Paguate Mine, N.M.: Consultant letter with attachments dated August 14, 1981.

Hydro-Search, Inc., 1981c, Hydrology of the Jackpile-Paguate Mine Area, N.M.: Consultant Report dated October 9, 1981.

Johnson, A.I., 1967, Specific Yield - Compilation of Specific Yields for Various Materials: U.S. Geological Survey Water-Supply Paper 1662-D.

Moench, R. H., 1963a, Geologic Map of the Seboyeta Quadrangle, N.M.: U.S. Geological Survey Map GQ-207.

Moench, R. H., 1963b, Geologic Map of the Laguna Quadrangle, N.M.: U.S. Geological Survey Map GQ-208.

National Oceanic and Atmospheric Administration, 1973a, Monthly Averages of Temperature and Precipitation for State Climatic Division, 1941-70: National Climatic Center, Asheville, North Carolina.

______,1973b, Precipitation Frequency Atlas of the Western United States, Volume IV, New Mexico.

REFERENCES Continued

New Mexico State Engineer Office, 1956, Climatological Summary, New Mexico, Precipitation 1849-1954: Technical Report Number 6.

Sammis, T. W., and Gay, L. W., 1979, Evapotranspiration from an Arid Zone Plant Community: Journal of Arid Environments, Vol. 2, p.313-321.

Schlee, J. S., and Moench, R. H., 1963a, Geologic Map of the Moquino Quadrangle, N.M.: U.S. Geological Survey Map GQ-209.

Schlee, J. S., and Moench, R. H., 1963b, Geologic Map of the Mesita Quadrangle, N. M.: U.S. Geological Survey Map GQ-210.

Schneider, K. L. and A. M. Platt, 1974, High Level Radioactive Waste Management Alternatives: Battelle Northwest Laboratories.

Summers, W. K., 1969, Analysis of Bailer Tests and Analysis of Pumping Test Well 2652, North Wind Whip Area, Laguna Reservation, Valencia County, N.M.: Report by the New Mexico Tech Research Foundation, Soccoro, N.M.

Tuan, Yi-Fu, Everard, Cyril E., Widdison, Jerold G., and Bennett, Iven, 1973, The Climate of New Mexico: State Planning Office, Santa Fe, N.M.

U.S. Department of Interior, Bureau of Reclamation, 1977, Design of Small Dams, Washington: U.S. Government Printing Office.

U.S. Environmental Protection Agency, 1978, Radionuclide Interactions With Soil and Rock Media: Vol. 1, EPA 520/6-78-007.

U.S. Geological Survey, 1982, Hydrology of the Jackpile Uranium Mine, Northwestern New Mexico, as Related to Reclamation of Disturbed-Surface Areas: Draft open file report.

TABLE 1

STRATIGRAPHIC DESCRIPTION - JACKPILE-PAGUATE MINE

Age	Symbol	Unit	Estimated Thickness (Feet)	Lithologic Characteristics	Yield and Water-Bearing Properties
Quaternary	Q_e	Eolian and Alluvial deposits	0 - 70	Valley-fill deposits of unconsolidated silt, clay, sand, and gravel	Yields of 15 to 90 gpm reported in Paguate area near perennial streams. Water quality good.
	Q_c	Colluvial deposits	0 - 30	Talus, landslide blocks, and sheets of debris	Mostly above water table.
	Q_{Td}	Dikes and sills	0 - 10	Friable diabase	Unknown; presumed poor.
Cretaceous	K_m	Mancos Shale	1,020	Calcareous marine shale	
	K_{ms}	Tres Hermanos Member	(110)	Three fine- to medium-grained sandstone units 20, 30 and 60 feet thick in ascending order	Yields from Tres Hermanos range from 5 to 20 gpm. Water quality probably fair to good in vicinity.
	K_d	Dakota Sandstone	50	Carbonaceous shale and well-cemented sandstone	Not known to yield water to wells in area.
Jurassic	J_m	Morrison Formation	600-650		
	J_{mj}	Jackpile Sandstone	(0-200)	Fine- to coarse-grained sandstone and sparse mudstone	Yields of 8 to 34 gpm reported. Water quality fair to poor.
	J_{mb}	Brushy Basin Member	(300)	Mudstone with sparse clayey sandstone and limestone; lenticular sandstones usually less than 20 feet thick	Well No. 4 reportedly yielded 100 gpm from sand units; 25 gpm from Paguate Shop well. Quality fair to poor.
	J_{mw}	Westwater Canyon Member	(50)	Fine- to coarse-grained sandstone, friable to well-cemented	Yield of 5 gpm reported in Well No. 5; quality poor.
	J_{mr}	Recapture Member	(50-100)	Mudstone, siltstone, and sandstone	Not known to yield water to wells in area.
	J_b	Bluff sandstone	280	Fine to medium-grained sandstone	Yields of 2 to 10 gpm reported. Quality poor.
	J_s	Summerville Formation	120	Mudstone and very fine- to fine-grained sandstone	Not known to yield water to wells in area.
	J_t	Todilto Formation	85	Limestone, gypsum and anhydrite	Not known to yield water to wells in area.
	J_e	Entrada Sandstone	300	Very fine- to medium-grained sandstone and siltstone	Yield of 5 gpm reported in well south of area; 16 gpm reported in well producing from J_e and T_{Rc}. Quality believed poor.
Triassic	T_{Rc}	Chinle Formation	1,400	Siltstone and mudstone, with interbedded silty sandstone and some conglomeratic sandstone	Sandstones reported poor by Sohio in L-Bar 2 well. Probably poor yields and poor water quality.
Permian	P_{sa}	San Andres Limestone	100	Limestone, sandy limestone, and limey sandstone	No yield or significant porosity reported in L-Bar 2 well; 15 gpm reported from well near Mesita.
	P_g	Glorieta Sandstone	120	Sandstone and siltstone	Unknown.
		Yeso Formation	1,300	Sandstone, mudstone, evaporites and limestone. Lower part fine-grained sandstone.	Unknown.
		Abo Formation	700	Arkosic sandstone, siltstone and conglomerate	Unknown.
Pennsylvanian(?)			1,200	Arkose, conglomerate, limestone and shale	Unknown.
Precambrian				Granite, gneiss, metarhyolite, schist and greenstone	Unknown.

TABLE 2

PRE-MINING WATER LEVEL ELEVATIONS

Drill Hole Number	Coordinates (ft) North	Coordinates (ft) East	Date Measured	Water Level Elevation (ft)
FDH 5531	1,006,384	990,685	4/13/60	6072
FDH 5589	1,014,066	998,026	5/02/60	5967
FDH 5664	1,013,803	996,295	5/13/60	5968
FDH 5681	1,008,151	996,897	9/09/60	5940
FDH 5869	1,012,002	993,888	8/03/60	5974
DDH 1994	1,008,652	996,452	9/09/60	5942
MDH 771	1,004,607	987,850	2/12/59	6112
F 5664	1,013,803	996,595	4/16/60	5981
F 5871	1,011,582	993,889	7/28/60	5962
F 5973	1,009,003	995,498	1/12/60	5945
F 5974	1,009,000	994,700	1/19/61	5945
F 5877	1,014,137	998,421	9/20/60	5949
F 5873	1,014,170	998,413	7/18/60	5947
B PIT	1,007,990	1,005,117	12/02/58	5926
PD 786	1,009,100	995,900	1960	5949
D 1994	1,008,652	996,492	1960	5942
D 2000	1,007,958	997,295	1960	5936
F 5714	1,007,852	996,287	1960	5942
F 5733	1,007,744	995,492	1960	5949
F 5305	1,007,167	993,291	1960	5991

Source: Anaconda Minerals Company (1982a)

TABLE 3

PUMPING TEST DATA BY HSI*

Well Site	Saturated Thickness (ft)	Specific Capacity (gpm/ft)	Average Transmissivity (ft^2/day) Pumped Well	Average Transmissivity (ft^2/day) Observation Well	Average Hydraulic Conductivity (ft/day) Pumped Well	Average Hydraulic Conductivity (ft/day) Observation Well	Average Storage Coefficient
M-1	94	0.06	4.9	10.7	0.05	0.11	4.5×10^{-4}
M-2	90	0.12	12.4	22.2	0.14	0.25	1.6×10^{-4}
M-3	108	0.29	46.1	53.1	0.43	0.49	2.8×10^{-4}
M-10	38	0.13	10.8	19.3	0.28	0.51	3.9×10^{-5}
M-14	114	0.01	0.53	1.1	0.005	0.01	1.0×10^{-4}
M-16	53	0.03	1.7	9.5	0.18	0.18	2.3×10^{-4}
M-21	83	0.01	0.27	1.5	0.02	0.02	2.2×10^{-4}

* Note: All wells completed in Jackpile Sandstone

Source: Hydro-Search, Inc., 1981a

TABLE 4

PUMPING TEST DATA BY USGS

Well Site	Aquifer*	Saturated Thickness (ft)	Specific Capacity (gpm/ft)	Average Transmissivity (ft^2/day)	Average Hydraulic Conductivity (ft/day)	Average Storage Coefficient
M-2	J_{mj}	93	0.14	26	0.28	1.9×10^{-4}
M-3	J_{mj}	120	0.25	47	0.39	2.7×10^{-4}
M-4C	Qal	19	4.5	410	22.	$19. \times 10^{-4}$
M-25	Jmbs	60	-	20	0.33	1.0×10^{-4}

* Aquifer: J_{mj} = Jackpile Sandstone

Qal = Alluvium

Jmbs = Sandstone bed in lower Brushy Basin Member

Source: U.S. Geological Survey (1982)

TABLE 5

WATER LEVEL ELEVATIONS

Well I.D.	Water Elevation (ft)	Date	Water Elevation (ft)	Date
M-1	6002.2	4/15/82	6004.4	12/16/82
M-2	5969.6	4/14/82	5971.8	12/16/82
M-3	5924.9	4/14/82	5926.2	12/15/82
M-4	5896.1	4/22/82	5897.2	12/15/82
M-4A	5896.2	4/13/82	-	-
M-4B	5896.4	4/22/82	-	-
M-4C	5896.8	4/22/82	-	-
M-5	6016.7	7/12/82	6019.9	11/15/82
M-6	5975.1	4/15/82	5979.6	12/18/82
M-7	5944.0	7/12/82	5951.1	11/16/82
M-8	5943.3	4/15/82	5944.7	11/16/82
M-9	5927.9	4/30/82	5929.5	11/15/82
M-10	5959.1	4/20/82	5959.5	11/16/82
M-11	5916.7	4/20/82	5921.0	11/18/82
M-11A	5960.4	4/20/82	-	-
M-12	5924.9	4/20/82	5921.0	11/16/82
M-14	5925.9	4/13/82	5937.3	12/17/82
M-15	5933.8	4/22/82	5954.2	11/18/82
M-16	5910.0	4/20/82	5911.0	12/15/82
M-19	5931.8	4/13/82	5934.1	11/18/82
M-20	5924.9	4/20/82	5924.9	12/19/82
M-21	5961.7	4/14/82	5961.7	12/17/82
M-22	5982.4	4/29/82	5984.3	11/29/82
M-23	5957.5	4/30/82	5959.7	11/16/82
M-25	5894.1	4/20/82	5910.7	11/18/82
M-26	5889.1	4/20/82	5881.4	11/29/82
3-A	5958.6	1/ /80		
Sohio LJ205	6066	10/ /71		
Sohio A-1	6000	5/ /74		

TABLE 6

SUMMARY OF CASES

Case	Name	Mode	Purpose
1	Pre-mining (Calibration)	Steady-State 2-D Plan View	Calibrate model to pre-mining water levels. Estimate head and flow distribution prior to mining.
2	During Mining (Verification)	Transient 2-D Plan View	Check modeled water levels against observed at end of mining period.
3	Post-mining, Long-term	Steady-State 2-D Plan View	Estimate long-term head and flow distribution after reclamation.
3.1 and 3.2	Post-mining, long-term - Sensitivity	Steady-State 2-D Plan View	Test sensitivity to backfill permeability. Same as Case 3 except: Case 3.1: Backfill K=20 ft/day Case 3.2: Backfill K= 2 ft/day
3.3 and 3.4	Post-mining, Long-term - Sensitivity	Steady-State 2-D Plan View	Test sensitivity to infiltration through pit backfill. Same as Case 3. Case 3.3: Pit infiltration = .044 in/yr Case 3.4: Pit infiltration = 0.12 in/yr
3.5	Post-mining, long-term -	Steady-State 2-D Plan View	Test water levels in N. Paguate Pit with in-pit dam.
4	Post-mining	Transient 2-D Plan View	Estimate time for water levels to recover in pits.

TABLE 7

MATERIAL PROPERTIES

Material	Case 1 Pre-Mining K (ft/d)	Case 2 During Mining K (ft/d)	Case 2 During Mining Sy	Case 2 During Mining Ss (ft^{-1})	Cases 3 and 4 Post-Mining K (ft/d)	Cases 3 and 4 Post-Mining Sy	Cases 3 and 4 Post-Mining Ss (ft^{-1})
1 - Jackpile Sandstone	0.25	0.25	0.2	2.5×10^{-6}	0.25	0.2	2.5×10^{-6}
2 - Alluvium	22.	22.	0.3	-	22.	0.3	-
3 - Backfill/Jackpile Sandstone	0.10	*	0.2	2.5×10^{-6}	190.	0.3	-
4 - P-10 Underground Mine	0.10	*	0.2	2.5×10^{-6}	190.	0.3	-
5 - Jackpile Sandstone	0.10	0.10	0.2	2.5×10^{-6}	0.10	0.2	2.5×10^{-6}
6 - Backfill/Jackpile Sandstone	0.25	*	0.2	2.5×10^{-6}	190.	0.3	-
7 - Backfill/Jackpile Sandstone	0.05	*	0.2	2.5×10^{-6}	190.	0.3	-
8 - Jackpile Sandstone	0.05	0.05	0.2	2.5×10^{-6}	0.05	0.2	2.5×10^{-6}

Key:
K = Hydraulic conductivity
Sy = Specific yield
Ss = Specific storage
* Constant heads used in pits or underground mine if excavation is below ground water level - otherwise pre-mining conductivity is used.

TABLE 8

PREDICTED POST-MINING GROUND WATER ELEVATIONS

Location	Node	Pre-Mining (Case 1)	Post-Mining (Case 3)	Post-Mining Sensitivity Analysis (Case 3.1)	(Case 3.2)	(Case 3.3)	(Case 3.4)	(Case 3.5)	Planned Backfill Level*
Jackpile Pit	[33,17]	5944	5929	5928	5930	5935	5945	5929	5938 - 5942
	[31,14]	5922	5929	5928	5927	5935	5945	5929	
South Paguate Pit	[17,19]	5969	5983	5980	5973	5984	5985	5983	5996 - 6003
	[13,19]	6011	5985	5994	6009	5986	5987	5985	
North Paguate Pit	[22,21]	5953	5975	5966	5956	5975	5975	5948	5955 - 5965
	[21,22]	5967	5976	5972	5967	5976	5976	5979	
P-10 Underground	[10,20]	6070	6055	6058	6064	6055	6057	6055	NA

* Approximate range of lower parts of backfill

TABLE 9

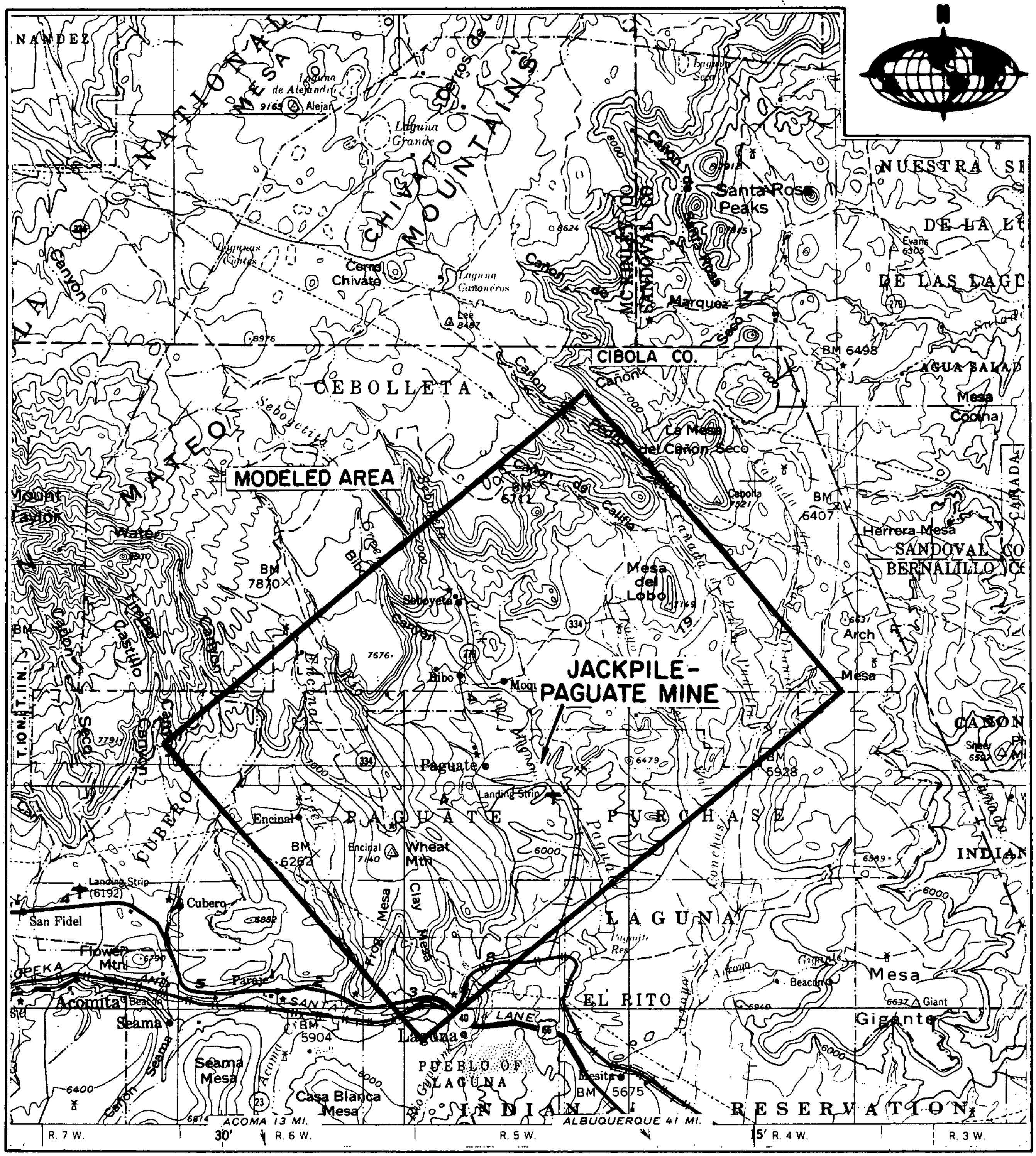
MONTHLY PRECIPITATION AND RUNOFF ESTIMATES

Month	ET[1]	2 Year P	2 Year RO	5 Year P	5 Year RO	10 Year P	10 Year RO	25 Year P	25 Year RO	50 Year P	50 Year RO	100 Year P	100 Year RO
		Recurrence Interval of Precipitation[2] and Subsequent Maximum Estimated Runoff[3]											
January	0.0	0.2	0.0	0.6	0.0	0.8	0.0	1.0	0.01	1.2	0.04	1.2	0.04
February	0.2	0.3	0.0	0.6	0.0	0.8	0.0	0.9	0.0	1.0	0.01	1.0	0.01
March	0.6	0.2	0.0	0.6	0.0	0.9	0.0	1.1	0.02	1.2	0.04	1.3	0.06
April	1.1	0.2	0.0	0.7	0.0	1.1	0.02	1.7	0.2	2.1	0.3	2.5	0.5
May	3.0	0.2	0.0	1.1	0.02	1.9	0.2	2.9	0.7	3.5	1.1	4.1	1.5
June	4.3	0.5	0.0	1.4	0.08	1.9	0.2	2.5	0.5	2.8	0.7	3.1	0.9
July	5.0	1.5	0.1	2.2	0.4	2.7	0.6	3.2	0.9	3.6	1.2	4.0	1.4
August	4.4	1.5	0.1	2.5	0.5	3.1	0.9	3.8	1.3	4.3	1.7	4.8	2.0
September	3.0	1.2	0.04	2.3	0.4	2.6	0.6	2.7	0.6	2.7	0.6	2.7	0.6
October	1.7	0.5	0.0	1.3	0.06	1.7	0.2	2.1	0.3	2.2	0.4	2.4	0.5
November	0.5	0.1	0.0	0.6	0.0	1.1	0.02	1.9	0.2	2.6	0.6	3.3	1.0
December	0.2	0.2	0.0	0.8	0.0	1.2	0.04	1.7	0.2	2.2	0.4	2.3	0.4

NOTES:

ET = Potential evapotranspiration (in)
P = Precipitation (in)
RO = Runoff (in)

1) Adapted from Tuan and others (1973) by prorating Albuquerque data to conditions at the site.
2) Precipitation in inches, based on the period 1927 to 1970 (New Mexico State Engineer Office, 1956, and NOAA, 1973) and Log Pearson III analysis (Haan, 1977).
3) Estimated by SCS methods (U.S. Dept. of Interior, 1977)



SCALE IN MILES

0 2 4 6

LOCATION MAP

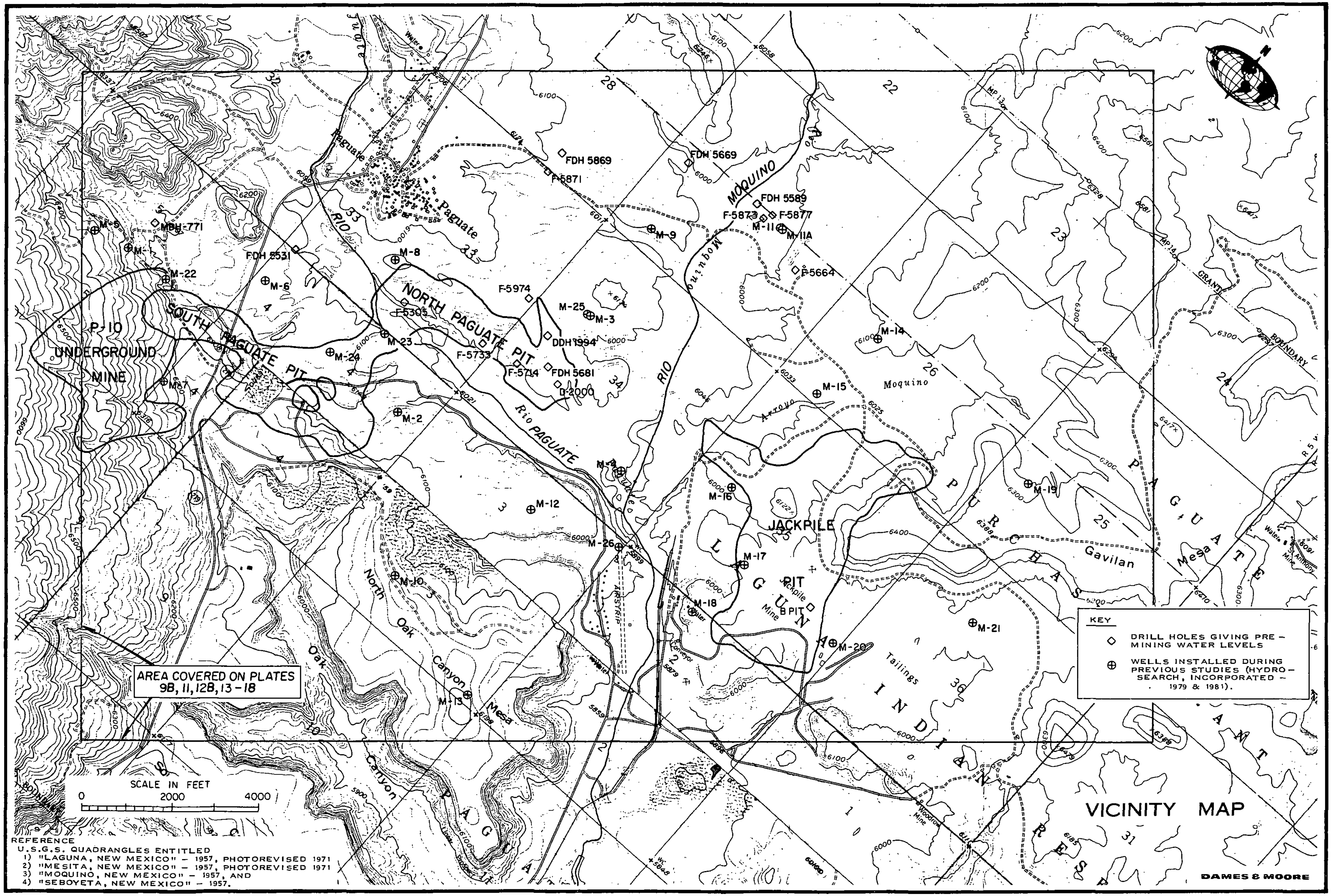
REFERENCE
U.S.G.S. 1:250,000 MAP SERIES
ENTITLED "ALBUQUERQUE, N.M."-
DATED 1963.

DAMES & MOORE

REVISIONS BY DATE

BY DATE FILE 04010-088

CHECKED BY GWC



REFERENCE
U.S.G.S. QUADRANGLES ENTITLED
1) "LAGUNA, NEW MEXICO" - 1957, PHOTOREVISED 1971
2) "MESITA, NEW MEXICO" - 1957, PHOTOREVISED 1971
3) "MOQUINO, NEW MEXICO" - 1957, AND
4) "SEBOYETA, NEW MEXICO" - 1957.

DAMES & MOORE

PLATE 2

MAPS NOT COPIED

APPENDIX A

APPENDIX A

FIELD INVESTIGATIONS AND LABORATORY TESTING

APPENDIX A

FIELD INVESTIGATIONS AND LABORATORY TESTING

TABLE OF CONTENTS

boring during the final stages in the piezometer completion. The piezometers were constructed using 2-inch diameter, schedule 40 PVC casing and slotted screen. The PVC screens used were factory-slotted to 0.020 inches. In all the installations, a one- to two-foot long blank casing with an end cap was positioned below the screen to act as a sediment trap. The PVC casing/screen assemblies were joined using PVC cement and allowed to set at least five minutes, then tested, before being placed into the borehole.

Each piezometer was sand-packed using Colorado silica sand which was tremied into place to generally seven feet above the top of the screen. The depth of the top of the sand pack was then logged to determine its exact depth. A five foot bentonite seal was placed above the sand pack and the remaining annular space was then sealed using a mixture of backfill and bentonite slurry. The slurry was poured into the borehole from the surface. A protective PVC slip cap was placed on the casing at the surface and the piezometer identification was written on the inside and outside of the cap, as well as on the outside of the casing.

INSTALLATION OF MONITORING WELLS

Five monitoring wells were installed at five different sites which are all located in previously backfilled areas. The purpose of the monitor wells was to assess the hydrologic characteristics of the different backfill materials, including permeability, porosity and water levels. In addition, these wells were used to obtain samples of ground water within the existing backfill areas for chemical analysis in the laboratory and directly in the field.

Only one well was installed at each site except for site B which also had two piezometers installed nearby. The borings at each well site were geologically logged on the basis of the drill cuttings, drilling characteristics and from known geological data of the local area. A table summarizing elevations, location, casing size, and screened intervals are given on Table A-4. Detailed construction information and logs of each monitor well are given on Table A-5.

In addition to obtaining drill cuttings at each well site, brief slug injection tests were performed at various selected depths during the drilling operation. These data will be discussed in a following section.

MONITORING WELL CONSTRUCTION METHODS

The borings were drilled using air-rotary methods by Earl & Sons Drilling Company of Cedar Crest, New Mexico, using an Ingersoll-Rand TH-60 Paystar 5000 drilling rig. Monitor well C was drilled using an Ingersoll-Rand T-4 drilling rig and was completed with the TH-60 drilling rig.

Boring diameters ranged from 9 to 12 inches. Because of borehole sloughing and poor sample returns due to high permeabilty zones, 8-inch diameter steel casing was driven into the borehole at site C, and 10-inch diameter casing was driven into the borehole at site A. The other drill sites remained stable and maintained good sample returns due to the addition of a thick foam mixture and, therefore, did not require installation of steel casing. The steel casing was joined by welding and was pulled from site C during the final stages of construction. Several unsuccessful attempts were made to pull the 10-inch casing from site A. The casing was finally left in the boring.

Monitor wells C, D and F were constructed using 5 9/16-inch diameter steel casing and stainless steel Johnson well screen which were fastened by welding. At sites A and B, 6-inch diameter steel casing was installed to the bottom of the boring. A stainless steel Johnson well screen welded to an appropriately sized K packer was lowered to the bottom of the boring and the 6-inch casing was pulled back to expose the screen. In all of the monitor well installations, a 2-foot long blank casing with an end cap was welded below the screen to act as a sediment trap.

Each well was sand-packed using Colorado silica sand. The sand-pack was tremied into place and extended to between 7- and 20-feet above the top of the screen. The depth to the top of the sand-pack was then tagged to determine its exact depth. A 5-foot bentonite seal was placed above the sand-pack for flow in systems which are unconfined. Since it is not known whether the saturated zones penetrated by monitor wells D and F are fully confined, the results should, therefore, be taken as only estimates of the hydraulic properties. Analysis of the slug test data indicate permeabilities of 0.1 ft/day and 3.4 ft/day for wells F and D respectively.

DRAWDOWN TESTS

Short duration pumping tests were performed during the sampling program to estimate hydraulic conductivities in high yield monitor wells B and C. Wells were pumped for 60 to 90 minutes using a 2 hp submersible pump discharging 16.5 to 18.75 gallons per minute. Water levels were measured with an electric water level meter at specific times and recorded. Hydraulic properties were determined using formulas for unsteady state flow in unconfined aquifers by the method of Boulton (1954). Analysis of the drawdown data indicated transmissivities of 500 and 100,000 gallons per day per ft (gpd/ft) for wells B and C respectively.

SPECIFIC CAPACITY MEASUREMENTS

Specific capacity measurements were made on monitor wells B and C as well as on most existing Anaconda monitoring wells that were sampled for this project. Specific capacity tests measure the well yield (in gallons per minute) as a function of time and the hydraulic head (drawdown in feet) required to produce the measured yield. The method used to perform these tests began with the measurement of the static water level before the placement of the pump into the well. Once the pump was set, the well was pumped at a rate in which the drawdowns were not excessively rapid. Water levels and pumping rates were then recorded for various times. If the well pumped dry, the pumping rate was reduced until the water levels stabilized at some depth above the pump. The pumping rate and total drawdown were then measured and recorded. The duration of the pumping period was generally 30 to 60 minutes. Table A-9 summarizes the calculated results of the specific capacity tests.

were pumped prior to sampling until three casing volumes had been removed or when all measured field parameters stabilized.

Monitor wells F and A were not included in the laboratory analyses program because representative samples could not be obtained. An explanation is as follows. Well F was not sampled during the sampling period due to its low yield and unstabilized field parameters (i.e. pH and conductivity). The well was bailed dry every day during the sampling period and yielded only several gallons of water each time. After a week, measured field parameters indicated that water from this well still exhibited effects from the drilling operation. This included traces of foam in the water, and field parameters which changed after each bailing cycle. It was felt that a much larger quantity of ground water should be removed before reliable samples could be obtained.

Well A was not sampled because during the sampling and well testing portion of this study, it was found that this well also had a very low yield and pumped dry very rapidly. Since this was inconsistant with previous data which showed the well to be highly permeable, the problem was investigated. Sounding of the hole showed that the screen was not exposed to the aquifer, but had stuck inside the casing during the pull-back operation. Attempts to sample the well proved difficult due to the low yield and the presence of drilling foam which requires large amounts of water to be pumped out. In its present state, well A is not useful as a monitoring well, but does provide reliable information concerning water levels.

Rehabilitation of this well is possible, and would require the screen and K packer assembly to be pulled from the well. The well could then be cleaned out and the screen lowered back into its proper position exposed to the aquifer. Development and pumpage of the well could then provide water samples once all drilling fluid is removed.

BULK SAMPLE COLLECTION

Five-gallon bulk samples were collected from pond Z and from monitor well B, and a 10-gallon bulk sample was obtained from Anaconda monitor well M-6. The pond Z sample was a composite from the west and southwest sections of the pond. The well samples were collected after a pumping period of approximately one hour. These samples were all collected in 1-gallon containers, stored on ice, and shipped to CEP Laboratories for the geochemical testing program. Field water quality results from the bulk sample locations are listed on Table A-12. Laboratory results are given on Tables A-21A through A-21C.

SAMPLING OF SURFACE SOURCES

As part of the water sampling stage of this project, samples were collected from several surface sources located in the excavated pit areas (see Plate 3 for locations). Samples were obtained from ponds V, W, and Y and from seep X by means of a peristaltic pump. The tygon tubing used for sampling, had a float device attached which enabled the hose to be placed away from the edge of the pond, and also prevented the hose from sinking below three feet in depth and collecting excess silt. Pond Z, due to poor access, was sampled by collecting and hand-carrying several gallons of water to the vehicle to be filtered, and for field analysis. Table A-11 lists the laboratory water quality results for these surface sources. Table A-12 shows the results for field analyses.

METHODS USED FOR FIELD PARAMETER MEASUREMENTS

Field measurement techniques for pH, conductivity, temperature, Eh, alkalinity and dissolved oxygen are summarized as follows:

pH: A Hach Model 19000 temperature-compensated digital pH meter was used to make pH readings. The meter was calibrated prior to each measurement using two-buffer standardization methods with pH 4, 7, and/or 10 buffers. Measurement of pH was performed during the pumping of each well and recorded after values stabilized (usually after 30 to 60 minutes).

Conductivity: Markson Science Model 10-B temperature-compensated conductivity meter was used to make specific conductance measurements on site during the pumping of each well and recorded after values stabilized. Conductivity measurements are reported at 25°C. The meter was standardized with 720, 2500, or 6680 micromho/cm standard solution.

Temperature: A Cibachrome dial thermometer, or the dissolved oxygen meter was used to obtain temperature measurements in degrees centigrade. Temperature is reported to the nearest 0.1°C.

Eh: A Hach Model 19000 digital pH meter with a millivolt mode and range of -1999 to +1999 mV was used with a Markson No. 1202 combination Platinum/ Reference Electrode to make Eh readings. The probe was inserted in a flow chamber attached to the discharge line from wells which were pumped. The same procedure was used in sampling the surface water sources, where a peristaltic pump was used. In bailed wells, Eh was measured in the bailer. Readings were recorded after stabilization of values occurred. Prior to each measurement, the meter was standardized using the quinhydrone method (i.e. a saturated quinhydrone solution in pH 4 or 7 buffers).

Alkalinity: Potentiometric titrations were used to determine alkalinity. Samples were collected in the field, stored on ice, and titrated within 24-hours of collection. Potentiometric titrations were performed by titrating 50 ml of pressure filtered water sample with sulfuric acid to pH 8.3 and/or 4.5 endpoints. Total alkalinity as $CaCO_3$, hydroxide, carbonate, and/or bicarbonate contents in mg/l of each sample were determined using methods from Brown and others (1970, p.43).

Dissolved Oxygen: A temperature, salinity, and pressure compensated Yellow Springs Instrument Company (YSI) Model 57 dissolved oxygen meter and 50-foot YSI 5739 probe were used to measure dissolved oxygen. The probe was inserted in a flow chamber attached to the discharge line from wells which were pumped. The same procedure was used in sampling the surface water sources, where a peristaltic pump was used. In bailed wells dissolved oxygen was measured in the bailer. Prior to each measurement, the meter was standardized using the manufacturer's instructions for air calibration. Dissolved oxygen concentrations reported in the accompanying tables are in parts per million (ppm).

WATER QUALITY SAMPLE PRESERVATION AND HANDLING

Each water quality sample sent to CEP Labs for analysis consisted of three bottles:

1. A 1,000 ml plastic bottle filled with raw (unfiltered) water. This bottle was analyzed for bicarbonate, carbonate, total dissolved solids, silica, chloride, specific conductance, fluoride, and sulfate.

2. A 200 ml glass bottle with sulfuric acid as a preservative filled with water filtered through a 0.45 micron filter. This sample was analyzed for phosphate (as P), nitrogen and nitrate (as N).

3. A 4,000 ml cubitainer with nitric acid as a preservative filled with water filtered through a 0.45 micron filter. This sample was used for analysis of metals.

Each set of sample bottles was stored on ice in a cooler, and freighted to the laboratory to insure that 24-hour holding times for some parameters would not be exceeded.

FIELD OBSERVATIONS

GENERAL

The stratigraphy in all the pits consists generally of Jackpile Sandstone which is overlain by 50 feet of Dakota Sandstone. The Dakota Sandstone in turn is overlain by a varying thickness of Mancos Shale. The contact between the Jackpile Sandstone and overlying units is very apparent. The Jackpile Sandstone is a white to light greenish gray, friable, fine to medium sandstone, which in hand specimen appears to have a low to moderately low permeability. The overlying units, on the other hand, are dark gray to brownish gray, well cemented, shales and sandstones of varying thicknesses. In hand specimen these units appear to have a very low to low permeability.

SOUTH PAGUATE PIT

The central part of the South Paguate Pit, which is scheduled to be backfilled, is roughly a square shape. During the peak mining period, this pit was connected to excavations to the northwest, northeast, and southeast, but has been subsequently isolated from them by backfill operations. The western and southern walls along with a man-made mesa in the northeast corner are composed of bedrock. The entire northern wall and the southeast wall are composed of backfill materials. The depth of the pit is between 200 and 250 feet, and will be filled approximately half-way after backfilling is completed. Access to the pit area is in the northeast corner.

The bottom of the pit area is occupied by two surface impoundments. A large lower pond is situated in the southeast corner of the pit area and is present throughout the year presumably due to ground water infiltration and direct runoff into the pit area. This pond was included in the water sampling program and is identified on Tables A-11 and A-12 as pond V. A slightly smaller upper pond is located east of and adjacent to the lower pond. This pond is approximately 30 feet higher than the lower pond and is also present throughout the year. A barrier which is composed of Jackpile Sandstone separates the two ponds. A third pond which was much smaller than the other two was present during this study in the north-central portion of the pit. It was approximately 25 feet higher than the upper pond and reportedly is not present in the pit year-round.

The lower pond is bisected by a vertical diabase dike which trends north-south in the pit area. It is approximately 10 feet wide and appears in air photographs and geology maps to be of regional extent. Hand specimens of this material are dense, fine-grained and hard, which indicate very low primary permeabilities. Few small fractures were observed in this feature giving it only slightly higher secondary permeabilities. Another smaller dike is present in the eastern portion of the pit area. It is located east of the upper pond and also trends north-south. It is only several feet wide and of the same composition as the other larger dike. Due to a higher degree of fracturing in this structure, secondary permeabilities would seem likely to be higher than in the other larger, more massive dike structure.

No springs were visible along the lower walls of the South Paguate pit, although the presence of occasional mosses on the lower west wall indicated slight seepage was present. A large seepage front was present along the barrier separating the upper and lower ponds. The seepage was occurring along the lower half of the barrier which was composed of solid Jackpile Sandstone. It is probable most of the seepage front was due to infiltration between the two ponds.

NORTH PAGUATE PIT

The portions of the North Paguate pit which are scheduled to be backfilled are in the western half of the pit area. The excavated pit is roughly rectangular in shape with the long axis trending east-west. The proposed backfill areas can be divided into two areas. The first is located in the mid-western portion of the North Paguate Pit. The second is located west of, and is separated from the main pit by a large pile of backfill material. These separate proposed backfill areas are called the east backfill and west backfill areas, respectively, of the North Paguate Pit.

EAST BACKFILL AREA

In this report the proposed backfill area which is to the east of piezometer site G is called the east backfill area. It is a relatively large, roughly square-shaped pit which is approximately 150 feet deep. The west wall is backfill material which separates the east backfill area from the smaller west backfill area. The entire north wall is bedrock composed of Jackpile Sandstone overlain by Dakota Sandstone and Mancos Shale. The east wall is composed of recent backfill material. Access to the east backfill area is from a road cut through this backfill composing the east wall. The lower two-thirds of the south wall is composed of Jackpile Sandstone which is overlain by approximately 45 feet of alluvium from the Rio Paguate. Apparently the river channel was located in this area and was subsequently displaced by the mining operations to its present channel several hundred yards to the south. The lower 10 feet of the alluvium is composed of basalt cobbles and gravel with some sand, silt and clay. The upper 35 feet of the alluvium is layered clays, silts and sand. The elevation of the base of alluvium was surveyed (Table A-1) indicating an elevation of 5963 feet at the eastern edge of the exposure.

The bottom of the pit area is occupied by a large perennial surface impoundment which is bisected by a diabase dike. The western half of this pond was included in the sampling program and is referred to in Tables A-11 and A-12 as pond W. The dike which cuts through the pit is about 5 feet thick, dips approximately 45 degrees to the west and trends northwest-southeast. This dike was interesting in that it also exhibited sill-like characteristics along the north wall. Geologic maps and air photos show this structure to be of regional extent. Very low permeabilities are suggested by hand specimens and outcrop exposures.

Several seeps and springs were observed along the base of the pit area. A large spring is located along the west-central wall of the pit. It was flowing from the base of a large backfill pile at a rate of approximately 100 gallons per minute. This spring was also included in the sampling program and is referred to in Tables A-11 and A-12 as seep X. Several seeps were also observed flowing from Jackpile Sandstone along the base of the south and southwest walls. These seeps each had a flow estimated at less than one gallon per minute. No seeps or springs were observed upon the south wall of the pit, either in the Jackpile Sandstone or in the alluvium.

WEST BACKFILL AREA

The west backfill area, during the peak mining period, was directly connected to the main North Paguate Pit area. It has subsequently been isolated from the main pit area by a large pile of backfill material. Piezometer site G is located on this backfill barrier. The west backfill area is relatively small occupying less than one-eighth the area of the east backfill area. The shape of the pit is roughly rectangular with the long axis trending north-south. The entire east and south walls are backfill material as is the lower portion of the north wall. Most of the west wall and upper north wall are bedrock composed of sandstone and shales. The depth of the pit is approximately 100 feet. Access to this section of the North Paguate pit is poor and is inaccessible to any vehicular traffic.

The southeast part of the west backfill area is occupied by a surface impoundment which is present throughout the year. A spring is located in the southwest corner of the pit area at the base of a large backfill pile. Discharge was estimated between 5 to 10 gallons per minute into the surface impoundment. Two seeps were also observed along the base of the west wall of the pit area originating from the Jackpile Sandstone. The total yield of these seeps was estimated to be less than 1 gallon per minute.

JACKPILE PIT

The portions of the Jackpile pit which are scheduled to be backfilled are in the west-central and northern parts of the pit area. The proposed backfill areas can be divided into three main areas. These separate proposed backfill areas are called in this report; the north backfill area, the northwest backfill area, and the west-central backfill area.

NORTH BACKFILL AREA

The north backfill area, at the time of this report, had already been modified by backfill operations. The northern portion and western portions were already three-quarters backfilled. Monitor well D is located on the backfill pile composing the western portion. The areas which have not yet been modified by backfill are the east and southeast portions of the north backfill area. Access to this area was extremely difficult due to steep embankments and flooding at the base. No vehicular traffic was possible into the pit area. A large perennial pond is located at the base of the east portion of the north backfill area. This pond was included in the sampling program and was also the source of the surface water bulk sample. It was designated pond Z. Pond Z was unusual in that instead of a light brownish green color as in the other impoundments, this pond was a bright turquoise color. No seeps or springs were visible in this area.

NORTHWEST BACKFILL AREA

This pit is relatively smaller than the other two backfill areas occupying less than one-fourth the area of the north backfill area. During peak mining periods this pit was directly connected with the main Jackpile pit. It has subsequently been isolated from the main Jackpile pit by backfill operations. The bottom of the pit is occupied by a surface impoundment which is present year-round. No seeps or springs are present in this pit.

WEST-CENTRAL BACKFILL AREA

The west-central backfill area is a relatively large, roughly square-shaped pit. The entire west wall is composed of bedrock, while the north, east and south boundaries are composed of backfill. Access to the pit area is from the southeast corner and is accessible to vehicles.

The bottom of the pit is occupied by a large perennial surface impoundment which was included in the sampling program. This impoundment, has been referred to in this report as pond Y. No seeps or springs were visible in the pit area.

LABORATORY TESTING

INTRODUCTION

A laboratory testing program was conducted to supplement field and available laboratory test data for the site. Objectives of the lab program were to:

1. Chemically characterize waters from the backfill and from surface impoundments in the pits.

2. Geochemically characterize waste rock and protore which is to be used as backfill material.

3. Evaluate acid-forming and neutralization potential of the various backfill materials.

4. Evaluate the effects of leaching and absorption upon chemical concentrations of key species.

5. Evaluate physical properties of backfill materials and geologic formations from the pit area.

The program consisted of six tasks:

1. Detailed mineralogic identification of representative samples of site backfill/rock.

2. Measurement of cation exchange capacity, calcium carbonate equivalent, saturated paste pH, acid/base potential, sulfur content and form (pyritic, sulfate, organic, total), arsenic and selenium content in 30 backfill/rock samples.

3. Measurement of uranium and radium-226 content in 30 backfill/rock samples.

4. Measurement of moisture content, specific gravity, grain size, and permeability in 13 backfill/rock samples.

5. Analysis of water quality of samples from three monitor wells, four ponds, and a seep on the site.

6. Performance of batch equilibrium experiments to evaluate leaching and/or chemical attenuation of selected constituents.

MINERAL IDENTIFICATION

Quantitative mineralogical analyses of selected samples listed and visually described in Table A-13 were performed by Automatic X-Ray Systems, of Golden, Colorado, using X-ray diffraction and chemical analysis. The X-ray diffraction techniques provide a qualitative mineral identification and the chemical analyses provide data to determine normative (or calculated) mineral determination. The results of these analyses are presented in Table A-14.

GEOCHEMICAL CHARACTERIZATION OF BACKFILL MATERIALS

Samples listed in Table A-13 were submitted to Agricultural Consultants, Inc. of Brighton, Colorado for measurement of cation exchange capacity (CEC), extractable cations (i.e., Ca, Mg, Na, K and H), calcium carbonate equivalent, saturated paste pH, acid/base potential, sulfur content and form (pyritic, sulfate, organic, total) and arsenic and selenium content. Methods used are given in Richards (1954) for extractable cations and CEC by methods 18 and 19 (p. 100-101); CCE by method 23c (p. 105); and saturated paste pH by method 21a (p. 102). The method for determining acid/base potential is given in Smith and others (1974, p. 48-51). Arsenic and selenium methods of extraction are given by American Society of Agronomy (1965, Part 2). Pyritic, sulfate, and organic sulfur testing was done by the American Society of Testing and Materials (ASTM) Method D-2492-68. Total sulfur analysis was by ASTM Method D-3177-75. The results of these analyses are presented in Tables A-15 through A-17.

RADIOLOGICAL CHARACTERISTICS

Radiological analyses were performed on samples listed in Table A-13 by Hazen Research, Inc. of Golden, Colorado for total uranium and radium-226. Fluorometric methods were used for U_3O_8 determinations as given in Canadian Department of Mines and Technical Surveys (1959). Radium-226 analysis were by Alpha Spectometry methods as given in Canadian Center for Mineral and Energy Technology (1975). Results of these analyses are presented in Table A-17.

PHYSICAL CHARACTERISTICS

Selected samples from proposed backfill piles during the field exploration program were tested in the Dames & Moore laboratory to evaluate their physical properties. The testing included moisture/density, grain size distribution, specific gravity, and permeability tests.

MOISTURE CONTENT AND DRY DENSITY DETERMINATIONS

The wet density and moisture content of selected recompacted samples were determined, and dry density was computed from this information. The dry density test results are presented on Table A-18. In general, backfill material had dry densities of from 87.0 to 96.3 pounds per cubic foot (pcf).

GRAIN SIZE DISTRIBUTION

Sieve and/or hydrometer tests were performed on selected sediments to aid in soil classification using ASTM* Method D-422. Results of these analyses are shown on Table A-19. Hydrometer tests are retained in our files.

SPECIFIC GRAVITY

Specific gravity of a sample is the ratio of the weight of the sample to the weight of an equal volume of distilled water. ASTM Method D854-58 was used to conduct the test. Results of the test are shown on Table A-18.

PERMEABILITY TESTS

Constant and falling head permeability tests were performed on selected recompacted samples representing various backfill materials in order to

* American Society for Testing and Materials

evaluate their vertical hydraulic conductivity characteristics. A general description of the test method is shown on Plate A-3, Method of Performing Percolation Tests. Results of these tests are tabulated on Table A-18.

BATCH EQUILIBRIUM TESTS

Batch equilibrium experiments were performed under controlled conditions to evaluate the chemical reactions between selected bulk ground water and surface water solutions with bulk samples of various backfill materials. The liquid/soil combinations are listed on Table A-20.

The soil/rock bulk samples were prepared by removing any rock pieces larger than a No.4 size from backfill samples. Chemical, physical and radiological tests have been performed on the selected backfill materials and described in earlier sections. Chemical analyses of each of the bulk water samples (M-6, well B and pond Z) were performed and the results listed on Tables A-21A through A-21C. The liquid/soil combinations were mixed at a 1:1 weight ratio with continuous shaking for a minimum of 48-hours and until pH and conductivity stabilized. The actual dry weight of the solids and the weight and volume of the liquid were recorded for each mixture. The supernatant liquid was then removed, filtered with a 0.45 micron filter; and then analyzed. Results of these analyses are listed on Tables A-21A, through A-21C.

Where given, the distribution coefficient (Kd) was calculated by comparing the final and initial concentration in solution for a constituent using:

$$Kd = \frac{A(Ci - Ce)}{BCe}$$

where

A = volume of solution, in ml;

B = weight of solid, in g;

Ci = initial influent concentration; and

Ce = final effluent concentration

Distribution coefficients are given in Table A-22. A positive Kd value indicates that the solid material is removing the ion from the solution and a negative Kd indicates that the ion is being contributed to the solution by the solid.

APPENDIX A

REFERENCES

American Society of Agronomy, 1965, Methods of Soil Analysis: American Society of Agronomy, Inc., Monograph No. 9, Part 2.

American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1981, Standard Methods for the Examination of Water and Wastewater, 15th ed.: New York, American Public Health Association, 1134P.

Boulton, N. S., 1954a, Unsteady radial flow to a pumped well allowing for delayed yield from storage: Internat. Assoc. Sci. Hydrology Pub. 37, p. 472-477.

Brown, Eugene, M. W. Skougstad, and M. J. Fishman, 1970, Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases: U.S. Geological Survey Techniques of Water Resources Investigations, Book 5, Chapter A1, 160 p.

Canadian Center for Mineral and Energy Technology, 1975, Determination of Radium-226 and Uranium Ores and Mill Products with Alpha Energy Spectometry: Can-Met Report 76-11.

Cooper, H. H., Bredehoeft, J. D., and Papadopoulos, I. S., 1967, Response of a finite-diameter well to an instantaneous charge of water: Water Resources Research, v. 3, no. 1, p. 263-269.

Department of Mines and Technical Surveys, 1959, Manual of Analytical Methods for Uranium Concentrating Plants: Mines Branch Monograph #866 Ottowa, Canada.

Ferris, J. G., and Knowles, D. B., 1963, The Slug-Injection Test for Estimating Coefficient of Transmissibility of an Aquifer: U. S. Geological Survey Water-Supply Paper 1536-I, p. 299-304.

Hvorslev, M. J., 1951, Time Lag and Soil Permeability in Ground Water Observations: U. S. Army Corps of Engineers, Waterways Experiment Station Bull. 36, Vicksburg, Mississippi.

Richards, L. A. (ed), 1954, Diagnosis and Improvement of Saline and Alkali Soils; U.S. Department of Agriculture Handbook No. 60, 160 p.

Smith, R. M., Grube, W. E. Jr., Arkle, T. Jr., Sobek, A., 1974, Mine Spoil Potentials for Soil and Water Quality: EPA PB-237-527, Cincinnati, Ohio.

TABLE A-1

ANACONDA SURVEY DATA

Well I.D.	Description	Anaconda Coordinates Northing	Anaconda Coordinates Easting	Elevation Top of Casing	Elevation Ground
A	6" Casing	1,003,301.00	989,285.27	6044.24	6041.25
B	6" Casing	1,004,471.35	994,585.05	6101.93	6099.20
B-I	2" PVC South	1,004,433.33	994,523.27	6102.89	6099.10
B-S	2" PVC North	1,004,444.41	994,512.57	6102.27	6099.10
C	5-9/16 Casing	1,007,541.70	996,667.36	5970.02	5966.50
D	5-9/16 Casing	1,011,837.77	1,004,180.93	5916.14	5913.50
E-D	2" PVC East	1,006,525.97	993,478.90	6038.04	6035.20
E-S	2" PVC West	1,006,528.90	993,472.93	6038.01	6035.20
F	5-9/16 Casing	1,006,250.30	993,538.02	6011.64	6008.60
G-D	2" PVC North	1,007,198.21	993,460.22	6031.15	6028.00
G-S	2" PVC South	1,007,195.11	993,463.00	6030.81	6028.00
H-D	2" PVC North	1,007,044.80	997,472.04	5969.69	5966.40
H-S	2" PVC South	1,007,033.59	997,476.16	5969.63	5966.40
I	2" PVC	1,006,018.95	993,582.27	6022.33	6019.30
J	2" PVC	1,006,608.68	994,100.35	6027.84	6024.00
Stake or Benchmark		**Northing**	**Easting**		**Elevation**
Base of Alluvium North Paguate Pit		1,007,301.07	995,164.32	-	5962.67
PP-31		1,006,694.49	996,933.67	-	5976.97
Pond		**Northing**	**Easting**	**Water Surface**	**Stake**
Pond W North Paguate Pit		1,007,895.00	994,125.00	5893.00	5895.20
Pond V South Paguate Pit		1,003,310.00	992,180.00	5943.54	5946.52
Pond Z North Jackpile Pit		1,011,642.01	1,004,743.77	5843.68	5890.65

NOTE: All elevations are referred to Anaconda Benchmark PP-31

TABLE A-2

SUMMARY OF WATER LEVELS AND ELEVATIONS

Well I.D.	Depth to Water (Top of Casing) (in feet)	Water Level Elevation (ft)	Measurement Date
A	61.42	5982.82	12/21/82
B	120.00	5982.59	12/13/82
B-I	dry @ 40.6	6062.3	12/13/82
B-S	dry @ 19.2	6083.1	12/13/82
C	40.33	5929.69	12/14/82
D	77.53	5838.61	12/21/82
E-D	dry @ 63.9	< 5974.1	12/13/82
E-S	dry @ 35.2	< 6002.8	12/13/82
F	44.04	5967.60	12/24/82
G-D	dry @ 94.3	< 5936.8	12/13/82
G-S	dry @ 45.4	< 5985.4	12/13/82
H-D	40.22	5929.47	12/09/82
H-S	40.22	5929.41	12/09/82
I	dry @ 50.5	< 5971.8	12/24/82
J	dry @ 52.8	< 5975.0	12/24/82
Pond W North Paguate Pit		5893.00	1/13/83
Pond V South Paguate Pit		5943.54	1/13/83
Pond Z North Jackpile Pit		5843.68	1/17/83

TABLE A-3
PIEZOMETER CONSTRUCTION DETAILS

Well I.D.	Well Size (in.)	Ground Elevation (ft.)	Top of PVC Casing Elevation (ft.)	Intake Zone Elevations		Intake Zone Depths		Location Anaconda Coordinates (ft.)
				Top (ft.)	Bottom (ft.)	Top (ft.)	Bottom (ft.)	
B-I	2.0	6099.10	6102.89	6068.10	6063.10	31	36	N. 1,004,433.33 E. 994,523.27
B-S	2.0	6099.10	6102.27	6089.10	6084.10	10	15	N. 1,004,444.41 E. 994,512.57
E-D	2.0	6035.20	6038.04	5980.20	5975.20	55	60	N. 1,006,525.97 E. 993,478.90
E-S	2.0	6035.20	6038.01	6009.70	6004.70	25.5	30.5	N. 1,006,528.90 E. 993,472.93
G-D	2.0	6028.00	6031.15	5943.00	5938.00	85	90	N. 1,007,198.21 E. 993,460.22
G-S	2.0	6028.00	6030.81	5993.00	5988.00	35	40	N. 1,007,195.11 E. 993,463.00
H-D	2.0	5966.40	5969.69	5896.90	5891.90	69.5	74.5	N. 1,007,044.80 E. 997,472.04
H-S	2.0	5966.40	5969.63	5925.40	5920.40	41	46	N. 1,007,033.59 E. 997,476.16
I	2.0	6019.3	6022.33	5977.30	5972.30	42	47	N. 1,006,018.95 E. 993,582.27
J	2.0	6024.00	6027.84	5980.00	5975.00	44	49	N. 1,006,608.68 E. 994,100.35

TABLE A-4

MONITOR WELL CONSTRUCTION DETAILS

Well I.D.	Well Size (in) I.D.	Ground Elevation (ft)	Top of Steel Casing Elevation (ft)	Intake Zone Elevations Top (ft)	Intake Zone Elevations Bottom (ft)	Intake Zone Depths Top (ft)	Intake Zone Depths Bottom (ft)	Location Anaconda Coordinates (ft)
A	6.0	6041.25	6044.24	-	-	-	-	N. 1,003,301.00 E. 989,285.27
B	6.0	6099.20	6102.59	5934.20	5929.20	165	170	N. 1,004,471.35 E. 994,585.05
C	5.0	5966.50	5970.02	5898.00	5893.00	68.5	73.5	N. 1,007,541.70 E. 996,667.36
D	5.0	5913.50	5916.14	5828.50	5823.50	85	90	N. 1,011,837.77 E. 1,004,180.93
F	5.0	6008.60	6011.64	5963.60	5958.60	45	50	N. 1,006,250.30 E. 993,538.02

TABLE A-5
LOGS OF BORINGS AND WELL CONSTRUCTION DATA

BORING SITE A

GEOLOGIC LOG:

Depths (in feet) from	to	
0.0	10.0	Silt (fill), with fine sand, clay, and gravel to boulder sized clasts, grayish brown.
10.0	16.0	Silt (fill), with fine sand and clay, trace to some gravel and boulder sized clasts, yellowish brown.
16.0	21.0	Boulders (fill), large, fine to medium grained sandstone well cemented and hard, light grayish brown.
21.0	25.0	Silt (fill), with fine sand and clay, trace gravel and boulder sized clasts, yellowish brown.
25.0	40.0	Gravel and boulder sized clasts (fill), silty, with some fine sand and clay, grayish brown.
40.0	51.0	Silt (fill), with clay and fine sand, trace gravel sized clasts, grades coarser with depth, grayish brown.
51.0	59.0	Gravel and boulder sized clasts (fill), with fine sand and some clay, grayish brown, voids present, lost circulation near bottom of this zone.
59.0	64.0	Sand (fill), fine grained, silty, with some clay, grayish brown.
64.0	74.0	Gravel and boulder sized clasts (fill), with fine sand and silt, and some clay, grayish brown, voids present, lost circulation from 67 to 74 feet.
74.0	76.0	Sandstone (Jackpile), fine to medium grained, friable and soft, pale grayish to white.

WELL CONSTRUCTION DATA:

MONITOR WELL A

Location: Anaconda Coordinates; N. 1003301.00 E. 989285.27
Elevation: Ground; 6041.25 feet Top of Casing; 6044.24 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air hammer to 65 feet, air rotory to 76 feet
Drilling Fluid: Air to 25 feet, Air with water injection to 58 feet, air with foam to 76 feet. Used American Mud "Versafoam".
Boring: Diameter; 12.0 inch Depth; 65 feet
Diameter; 9.9 inch Depth; 76 feet
Surface Casing: Diameter; 10.0 inch Depth; to 69.0 feet
Casing: Diameter; 6.0 inch Material; Steel, 0.156 inch wall
Depth; from ground to 70.0 feet
Screen: Diameter; 5.9 inch Material; Stainless steel wire wrapped with 0.025 inch slots.
Depth; from 65.0 to 70.0 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 63 to 76 feet
Bentonite Seal: Depth; from 58 to 63 feet
Surface Seal: Type; Neat cement grout
Depth; from 0 to 58 feet

REMARKS: Screen stuck inside casing
No chemical analyses available

TABLE A-5 (CONTINUED)

BORING SITE B

GEOLOGIC LOG:

Depths (in feet) from	to	
0.0	15.0	Sand (fill), fine to medium grained, silty, with some clay, trace to some gravel and boulder sized clasts, light greenish gray.
15.0	19.0	Gravel and boulder sized clasts (fill), with fine to medium grained sand, silt, and some clay, bit bouncing, light gray.
19.0	29.0	Sand (fill), fine to medium grained, silty, with some clay, some gravel to boulder sized clasts, light gray.
29.0	33.0	Gravel and boulder sized clasts (fill), with fine to medium grained sand, silt, some clay and dark gray volcanic clasts (dike material), bit bouncing, light gray.
33.0	76.0	Sand (fill), fine to medium grained, silty, with clay, some gravel to boulder sized clasts, light gray.
76.0	86.0	Gravel and boulder sized clasts (fill), with fine to medium grained sand, and some silt and clay, bit bouncing, much grayish green material.
86.0	107.0	Sand (fill), fine to medium grained, silty, with some clay, trace to some gravel and boulder sized clasts, light gray.
107.0	112.0	Gravel and boulder sized clasts (fill), with fine to medium grained sand,silt, and some clay, bit bouncing, much grayish green material.
112.0	129.0	Sand (fill), fine to medium grained, silty, with some clay, trace to some gravel and boulder sized clasts, light gray.
129.0	136.0	Gravel and boulder sized clasts (fill), with fine to medium grained sand, silt, and some clay, bit bouncing, light gray.
136.0	160.0	Sand (fill), fine to medium grained, silty, with some clay, some gravel and boulder sized clasts, light gray.
160.0	172.0	Gravel, coarse sand, and boulder sized clasts (fill), composed of dark volcanics (dike material) and light gray sandstone, lost circulation in this zone, much water.

WELL CONSTRUCTION DATA:

PIEZOMETER B-S

Location: Anaconda Coordinates; N. 1004444.41 E. 994512.57
Elevation: Ground; 6099.10 feet Top of Casing; 6102.27 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air rotory
Drilling Fluid: Air with water injection
Boring: Diameter; 6.0 inch Depth; 16.0 feet
Surface Casing: None

TABLE A-5 (CONTINUED)

SITE B (CONT.)

Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 10.0 feet and from 15.0 to 16.0 feet

Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 10.0 to 15.0 feet

Sand Pack: Type; #10-20 Fountain sand
Depth; from 7 to 16 feet

Bentonite Seal: Depth; from 4 to 7 feet

Surface Seal: Type; Bentonite slurry and backfill
Depth; from 0 to 4 feet

PIEZOMETER B-I

Location: Anaconda Coordinates; N. 1004433.33 E. 994523.27

Elevation: Ground; 6099.10 feet Top of Casing; 6102.89 feet

Drilling Co.: Earl and Sons Drilling Co.

Drilling Method: Air rotory

Drilling Fluid: Air with water injection

Boring: Diameter; 6.0 inch Depth; 37.0 feet

Surface Casing: None

Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 31.0 feet and from 36.0 to 37.0 feet

Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 31.0 to 36.0 feet

Sand Pack: Type; #10-20 Fountain sand
Depth; from 25 to 37 feet

Bentonite Seal: Depth; from 20 to 25 feet

Surface Seal: Type; Bentonite slurry with backfill
Depth; from 0 to 20 feet

MONITOR WELL B

Location: Anaconda Coordinates; N. 1004471.35 E. 994585.05

Elevation: Ground; 6099.20 feet Top of Casing; 6101.93 feet

Drilling Co.: Earl and Sons Drilling Co.

Drilling Method: Air rotory

Drilling Fluid: Air to 10 feet, Air with water injection to 15 feet, air with foam to 172 feet. Used Halliburton "Howco Suds".

Boring: Diameter; 9.8 inch Depth; 172 feet

Surface Casing: None

Casing: Diameter; 6.0 inch Material; Steel, 0.250 inch wall
Depth; from ground to 165.0 feet and from 170.0 to 172.0 feet

Screen: Diameter; 4.0 inch Material; Stainless steel wire wrapped with 0.035 inch slots
Depth; from 165.0 to 170.0 feet

Sand Pack: Type; #10-20 Fountain. sand
Depth; from 145 to 172 feet

Bentonite Seal: Depth; from 140 to 145 feet

Surface Seal: Type; Neat cement grout
Depth; from 0 to 140 feet

REMARKS: Complete chemical analyses available

TABLE A-5 (CONTINUED)

BORING SITE C

GEOLOGIC LOG:

Depths (in feet)

from	to	
0.0	30.0	Sand (fill),fine to medium grained, clayey, with silt, trace to some gravel and boulder sized clasts, greenish brown, grades to greenish gray with depth.
30.0	35.0	Gravel and boulder sized clasts (fill), clayey fine sand with silt, bit bouncing, clasts composed of Jackpile Ss, greenish gray.
35.0	40.0	Sand (fill), fine grained, clayey, with silt, greenish gray.
40.0	43.0	Gravel and boulder sized clasts (fill), clayey fine sand with silt, bit bouncing, greenish gray.
43.0	46.0	Sand (fill), fine grained, silty, with clay, greenish gray.
46.0	55.0	Gravel and boulder sized clasts (fill), clayey fine sand with silt, bit bouncing, greenish gray.
55.0	65.0	Silt (fill), clayey, with fine sand, trace gravel and boulder sized clasts, greenish gray.
65.0	74.0	Gravel, coarse sand, and boulder sized clasts (fill), trace to some fine sand and silt, clasts composed of Jackpile Ss with some dark gray volcanics (dike material), greenish gray, much water in this zone.
74.0	76.0	Sandstone (Jackpile), fine grained, with some silt, and trace medium sand, pale gray to white, smooth drilling.

WELL CONSTRUCTION DATA:

MONITOR WELL C

Location: Anaconda Coordinates; N. 1007541.70 E. 996667.36
Elevation: Ground; 5966.50 feet Top of Casing; 5970.02 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air rotory
Drilling Fluid: Air with water injection
Boring: Diameter; 9.0 inch Depth; 76.0 feet
Surface Casing: None
Casing: Diameter; 5.9 inch Material; Steel, 0.203 inch wall
Depth; from ground to 68.5 feet and from 73.5 to 75.5 feet
Screen: Diameter; 5.9 inch Material; Stainless steel wire wrapped with 0.025 inch slots
Depth; from 68.5 to 73.5 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 60 to 76 feet
Bentonite Seal: Depth; from 55 to 60 feet
Surface Seal: Type; Neat cement groat
Depth; from 0 to 55 feet

REMARKS: Complete chemical analyses available

TABLE A-5 (CONTINUED)

BORING SITE D

GEOLOGIC LOG:

Depths (in feet) from	to	
0.0	2.0	Gravel sized clasts (fill), silty, with fine sand, brown.
2.0	11.0	Gravel and boulder sized clasts (fill), sandy, with silt, trace to some of clay, light brown.
11.0	55.0	Sand (fill), fine to medium grained, with some silt, trace to some clay and boulder sized clasts, clasts composed of Jackpile Ss and dark shales, brown to grayish brown.
55.0	70.0	Gravel and boulder sized clasts (fill), fine sand and silt, with clay, bit bouncing, greenish grey.
70.0	103.0	Gravel and boulder sized clasts (fill), fine sand and silt, with clay, many green clasts present, bit bouncing, gray, with some lenses greenish gray.
103.0	105.0	Sandstone (Jackpile), fine sand, with silt, and trace to some clay, drilling hard and smooth, tan to pale gray.

REMARKS: A boring drilled near this site hit voids and lost circulation from 70 to 103 feet.

WELL CONSTRUCTION DATA:

MONITOR WELL D

Location: Anaconda Coordinates; N. 1011837.77 E. 1004180.93
Elevation: Ground; 5913.50 feet Top of Casing; 5916.14 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air rotory
Drilling Fluid: Air with water injection to 20 feet, air with foam to 105 feet. Used American Mud "Versafoam".
Boring: Diameter; 9.8 inch Depth; 100 feet
Boring: Diameter; 9.0 inch Depth; 105 feet
Surface Casing: None
Casing: Diameter; 5.9 inch Material; Steel, 0.203 inch wall
Depth; from ground to 85.0 ft. and from 90.0 to 92.0 feet
Screen: Diameter; 5.9 inch Material; Stainless steel wire wrapped with 0.025 inch slots.
Depth; from 85.0 to 90.0 feet
Sand Pack: Type; #10-20 Fountain sand
Depth; from 60 to 105 feet
Bentonite Seal: Depth; from 55 to 60 feet
Surface Seal: Type; Neat cement grout
Depth; from 0 to 55 feet

REMARKS: Complete chemical analyses available

TABLE A-5 (CONTINUED)

BORING SITE E

GEOLOGIC LOG:

Depths (in feet) from	to	
0.0	5.0	Sand (fill), fine to medium grained, with silt and clay, trace to some gravel and boulder sized clasts, yellowish brown.
5.0	18.0	Silt (fill), clayey, with fine sand, trace to some gravel sized clasts composed of dark sandstone and shale, dark brown.
18.0	30.0	Gravel and boulder sized clasts (fill), clayey to silty, some fine sand, voids present, lost circulation, light brown color.
30.0	41.0	Silt (fill), fine sandy, with clay, trace to some gravel sized clasts, light brown.
41.0	50.0	Sand (fill), fine grained, silty, clayey, some gravel and boulder sized clasts, yellowish brown.
50.0	62.0	Silt (fill), with fine sand and clay, trace gravel sized clasts, dark grayish brown.
62.0	81.0	Sandstone (Jackpile), fine to medium grained, with some silt, light gray to white.

WELL CONSTRUCTION DATA:

PIEZOMETER E-S

Location: Anaconda Coordinates; N. 1006528.90 E. 993472.93
Elevation: Ground; 6035.20 feet Top of Casing; 6038.01 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air hammer
Drilling Fluid: Air with water injection
Boring: Diameter; 6.0 inch Depth; 32.5 feet
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 25.5 feet and from 30.5 to 32.5 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 25.5 to 30.5 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 18 to 32.5 feet
Bentonite Seal: Depth; from 13 to 18 feet
Surface Seal: Type; Bentonite slurry with backfill
Depth; from 0 to 13 feet

TABLE A-5 (CONTINUED)

SITE E (CONT).

PIEZOMETER E-D

Location: Anaconda Coordinates; N. 1006525.97 E. 993478.90
Elevation: Ground; 6035.20 feet Top of Casing; 6038.04 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air hammer
Drilling Fluid: Air with water injection
Boring: Diameter; 6.0 inch Depth; 82 feet (backfilled to 62 feet)
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 55.0 feet and from 60.0 to 61.5 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factort cut slots
Depth; from 55.0 to 60.0 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 47 to 62 feet
Bentonite Seal: Depth; from 42 to 47 feet
Depth; from 62 to 82 feet
Surface Seal: Type; Bentonite slurry with backfill
Depth; from 0 to 42 feet

BORING SITE F

GEOLOGIC LOG:

Depths (in feet) from	to	
0.0	5.0	Sand (fill), fine grained, silty, with some clay, trace gravel and boulder sized clasts, brown.
5.0	18.0	Sand (fill), fine to medium grained, silty, with some clay and boulder sized clasts, grayish brown.
18.0	22.0	Silt (fill), with fine sand, some silt and boulder sized sized clasts of decomposed shale, dark gray.
22.0	37.0	Gravel and boulder sized clasts (fill), silty, with fine sand, and some clay, clasts composed of dark sandstone and shale, lost circulation at 35 feet, gray to brownish gray.
37.0	40.0	Sand (fill), fine to medium grained, silty, with trace to some clay, and trace gravel sized clasts. gray.
40.0	46.0	Sand (fill), fine grained, with clay, and some silt, medium sand, and gravel sized clasts, light gray.
46.0	48.0	Sand (fill), fine to medium grained, with gravel and boulder sized clasts, some silt and clay, light gray.
48.0	52.0	Sandstone (Jackpile), fine to medium grained, with some silt, pale gray to white.

SITE F (CONT.)

WELL CONSTRUCTION DATA:

MONITOR WELL F

Location: Anaconda Coordinates; N. 1006250.30 E. 993538.02
Elevation: Ground; 6008.60 feet Top of Casing; 6011.64 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air rotory
Drilling Fluid: Air with water injection to 35 feet, air with foam to 52 feet. Used American Mud "Versafoam".
Boring: Diameter; 9.0 inch Depth; 52.0 feet
Surface Casing: None
Casing: Diameter; 5.9 inch Material; Steel, 0.203 inch wall
Depth; from ground to 45.0 feet and from 50.0 to 51.5 feet
Screen: Diameter; 5.9 inch Material; Stainless steel wire wrapped with 0.025 inch slots
Depth; from 45.0 to 50.0 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 38 to 52 feet
Bentonite Seal: Depth; from 33 to 38 feet
Surface Seal: Type; Neat cement grout
Depth; from 0 to 33 feet

REMARKS: Only field chemical analyses available

BORING SITE G

GEOLOGIC LOG:

Depths (in feet)

from	to	
0.0	8.0	Silt (fill),fine sand, with clay, some gravel and boulder sized clasts, dark brownish gray.
8.0	15.0	Gravel and boulder sized clasts (fill), clayey, with fine sand and silt, dark brownish gray.
15.0	35.0	Sand (fill), silty, with clay, trace to some gravel and boulder sized clasts, dark brownish gray.
35.0	42.0	Gravel and boulder sized clasts (fill), silty, with fine sand and clay, dark brownish gray.
42.0	54.0	Sand (fill), silty, with clay, trace to some gravel and boulder sized clasts, dark brownish gray.
54.0	61.0	Gravel and boulder sized clasts (fill), fine sand, with silt, and some clay, lost some circulation in this zone, dark brownish gray.
61.0	76.0	Silt (fill), fine sand, with clay, and some gravel sized clasts, dark brownish gray.
76.0	92.0	Gravel and boulder sized clasts (fill), fine sand, with some silt and clay, voids present, lost circulation in this zone.
92.0	96.5	Sandstone (Jackpile), fine grained, with some medium grains and silt, light yellowish white.

TABLE A-5 (CONTINUED)

SITE G (CONT.)

WELL CONSTRUCTION DATA:

PIEZOMETER G-S

Location: Anaconda Coordinates; N. 1007195.11 E. 993463.00
Elevation: Ground; 6028.00 feet Top of Casing; 6030.81 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air hammer
Drilling Fluid: Air with water injection
Boring: Diameter; 8.0 inch Depth; 42.0 feet
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 35.0 feet and from 40.0 to 42.0 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 35.0 to 40.0 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 28 to 42 feet
Bentonite Seal: Depth; from 23 to 28 feet
Surface Seal: Type; Bentonite slurry with backfill
Depth; from 0 to 23 feet

PIEZOMETER G-D

Location: Anaconda Coordinates; N. 1007198.21 E. 993460.22
Elevation: Ground; 6028.00 feet Top of Casing; 6031.15 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air hammer
Drilling Fluid: Air with water injection to 55 feet, air with foam to 96.5 feet. Used American Mud "Versafoam".
Boring: Diameter; 6.0 inch Depth; 96.5 feet
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 85.0 feet and from 90.0 to 92.0 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 85.0 to 90.0 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 78 to 96.5 feet
Bentonite Seal: Depth; from 73.0 to 78.0 feet
Surface Seal: Type; bentonite slurry with backfill
Depth; from 0 to 73 feet

TABLE A-5 (CONTINUED)

BORING SITE H

GEOLOGIC LOG:

Depths (in feet) from	to	
0.0	5.0	Clay, silty, with fine to medium sand, brown.
5.0	10.0	Sand, fine grained, silty, with some clay, yellowish brown.
10.0	15.0	Clay, with silt, and trace to some fine sand, grayish brown.
15.0	20.0	Sand, fine grained, silty, with thin layers of grayish brown clay, yellowish brown.
20.0	24.0	Gravel, fine, and coarse sand composed of rounded volcanics, silty, with fine sand, and trace clay, brown.
24.0	35.0	Sand, fine grained, with silt, and some clay, soft, grades with thin layers of coarse sand and fine gravel near bottom of this zone, yellowish brown.
35.0	51.0	Gravel, fine to coarse, with fine to coarse sand, silt, and trace to some clay, lost circulation near bottom of this zone, brown.
51.0	77.0	Sandstone (Jackpile), fine to medium grained, with trace to some silt, grades from light greenish gray near top to pale buff white with depth.

WELL CONSTRUCTION DATA:

PIEZOMETER H-S

Location: Anaconda Coordinates; N. 1007033.59 E. 997476.16
Elevation: Ground; 5966.40 feet Top of Casing; 5969.63 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air rotory
Drilling Fluid: Air with water injection
Boring: Diameter; 5.9 inch Depth; 52 feet (backfilled to 48 feet)
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 41.0 feet and from 46.0 to 48.0 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 41.0 to 46.0 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 33 to 48 feet
Bentonite Seal: Depth; from 28 to 33 ft.
Depth; from 48 to 52 feet
Surface Seal: Type; Bentonite slurry with backfill
Depth; from 0 to 28 feet

TABLE A-5 (CONTINUED)

SITE H (CONT.)

PIEZOMETER H-D

Location: Anaconda Coordinates; N. 1007044.80 E. 997472.04
Elevation: Ground; 5966.40 feet Top of Casing; 5969.69 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air rotory
Drilling Fluid: Air with water injection to 40 feet, air with foam to 77 feet. Used American Mud "Versafoam".
Boring: Diameter; 7.9 inch Depth; 50 feet
Diameter; 5.9 inch Depth; 77 feet
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 69.5 feet and from 74.5 to 77.0 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 69.5 to 74.5 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 60 to 77 feet
Bentonite Seal: Depth; from 55 to 60 feet
Surface Seal: Type; Bentonite slurry and backfill
Depth; from 0 to 55 feet

BORING SITE I

GEOLOGIC LOG:

Depths (in feet)

from	to	
0.0	21.0	Clay (fill), silty, with some fine to medium sand, trace to some gravel and boulder sized clasts, dark brownish gray.
21.0	30.0	Boulder and gravel sized clasts (fill), with fine sand, and some silt and clay, voids present, lost circulation from 25 to 30 feet. dark brownish gray.
30.0	40.0	Silt (fill), clayey, with some fine sand, trace to some gravel and boulder sized clasts, brownish gray.
40.0	45.0	Gravel and boulder sized clasts (fill), clayey, with silt and fine sand, clasts composed of dark sandstone and shale, dark brownish gray.
45.0	48.0	Silt (fill), clayey, with some fine sand and gravel sized clasts, dark brownish gray.
48.0	53.0	Sandstone (Jackpile), fine grained, with trace to some silt, light gray to white.

WELL CONSTRUCTION DATA:

PIEZOMETER I

Location: Anaconda Coordinates; N. 1006018.95 E. 993582.27
Elevation: Ground; 6019.30 feet Top of Casing; 6022.33 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air hammer
Drilling Fluid: Air with water injection to 30 feet, air with foam to 53 feet. Used American Mud "Versafoam".

SITE I (CONT.)

Boring: Diameter; 6.0 inch Depth; 40 feet
Diameter; 5.9 inch Depth; 53 feet (backfilled to 49 feet)
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 42.0 feet and from 47.0 to 49.0 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 42 to 47 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 36 to 49 feet
Bentonite Seal: Depth; from 31 to 36 feet
Depth; from 49 to 53 feet
Surface Seal: Type; Bentonite slurry with backfill
Depth; from 0 to 31 feet

BORING SITE J

GEOLOGIC LOG:

Depths (in feet)

from	to	
0.0	5.0	Clay (fill), silty, with some gravel sized clasts, trace to some fine sand, brown color.
5.0	10.0	Clay, silty, with some fine sand, light gray brown.
10.0	15.0	Silt, clayey, with some fine sand, light grayish brown.
15.0	21.0	Clay, silty, with some fine sand, light gray brown.
21.0	30.0	Silt, clayey, with some fine sand, yellowish brown.
30.0	50.0	Silt, with clay and some fine sand, dark brown.
50.0	53.0	Sandstone (Jackpile), fine to medium grained, with trace to some silt, pale gray to white.

WELL CONSTRUCTION DATA:

PIEZOMETER J

Location: Anaconda Coordinates; N. 1006608.68 E. 994100.35
Elevation: Ground; 6024.00 feet Top of Casing; 6027.84 feet
Drilling Co.: Earl and Sons Drilling Co.
Drilling Method: Air hammer
Drilling Fluid: Air with water injection
Boring: Diameter; 6.0 inch Depth; 53 feet (backfilled to 50 feet)
Surface Casing: None
Casing: Diameter; 2.0 inch Material; Schedule 40 PVC
Depth; from ground to 44.0 feet and from 49.0 to 50.0 feet
Screen: Diameter; 2.0 inch Material; Schedule 40 PVC with 0.020 inch factory cut slots
Depth; from 44.0 to 49.0 feet
Sand Pack: Type; #16-30 Fountain sand
Depth; from 37 to 50 feet
Bentonite Seal: Depth; from 32 to 37 feet
Depth; from 50 to 53 feet
Surface Seal: Type; Bentonite slurry with backfill
Depth; from 0 to 32 feet

TABLE A-6

COMPARISON OF PERMEABILITY VALUES FROM PIEZOMETERS AND SELECTED MONITOR WELLS

Well I.D.	Well Type	Material Tested	Permeability Test Method	Permeability (ft/day)
B	Monitor Well	Backfill	TAD	13.
B-I	Piezometer	Backfill	CHIT	1.2
B-S	Piezometer	Backfill	CHIT	1.5
C	Monitor Well	Backfill	TAD	2,700.
D	Monitor Well	Backfill	SWT	3.4
E-D	Piezometer	Backfill	CHIT	1.3
E-S	Piezometer	Backfill	CHIT	31.
F	Monitor Well	Compacted Backfill	SWT	0.1
G-D	Piezometer	Backfill	CHIT	6.2
G-S	Piezometer	Backfill	CHIT	2.8
H-D	Piezometer	Jmj Ss	CHIT	0.4
H-S	Piezometer	Alluvium	CHIT	0.9
I	Piezometer	Backfill	CHIT	2.5
J	Piezometer	Alluvium	CHIT	0.9

Explanation:

TAD - Theis Aquifer Drawdown Test
CHIT - Constant Head Injection Test
SWT - Slug Withdrawal Test

TABLE A-7

RESULTS OF BRIEF INJECTION TESTS

Well I.D.	Depth (ft)	Relative Permeability*
A	25	Low
A	60	High
A	73	High
B	100	Low
B	170	High
C	22	Low
C	45	Low
C	70	High
D**	19	Low
D**	38	Low
D**	60	High
D**	103	High
F	40	High
F	51	Low

* See text for discussion
** First boring drilled at site D

TABLE A-8

CONSTANT HEAD INJECTION TEST RESULTS

Well I.D.	Tested Interval (ft)	Flow Rate (gpm)	Head (ft)	Permeability (ft/d)
B-I	25 - 37	3.4	29	1.2
B-S	7 - 16	1.5	12	1.5
E-D	47 - 62	2.8	19	1.2
E-S	19.5 - 32.5	21.8	7	31.
G-D	78 - 96.5	10.2	12	6.2
G-S	28 - 42	5.8	17	2.8
H-D	60 - 77	1.9	38	0.4
H-S	33 - 48	3.9	37	0.9
I	36 - 49	4.5	14	2.5
J	37 - 50	4.1	42	0.9

TABLE A-9

SPECIFIC CAPACITY TEST RESULTS

Well I.D.	Pumping Rate (gpm)	Drawdown (ft)	Time (Minutes)	Specific Capacity (gpm/ft)
B	16.7	9.7	10	1.7
B	16.7	13.0	60	1.3
C	18.7	0.1	10	190
C	18.7	0.1	57	190
M-1	6.2	43.0	38	0.14
M-2	8.3	40.6	39	0.20
M-2	8.3	40.1	46	0.21
M-3	12.5	19.1	17.5	0.65
M-3	12.5	21.9	32	0.57
M-4	4.2	37.0	36.5	0.11
M-6	3.2	28.7	49	0.11
M-16	1.1	63.1	50	0.02
M-16	1.1	64.1	56	0.02
M-21	4.3	77.2	41	0.06

TABLE A-10

CEP ROUTINE ANALYTICAL METHODS AND REFERENCES FOR WATER

Parameter	Method	Reference Code
Carbonate	Electrometric titration	A
Bicarbonate	Electrometric titration	A
Silica	Inductively coupled plasma	C
pH	Electrometic	A
Total Dissolved Solids	Gravimetric	A
Chloride	Silver Nitrate	A
Fluoride	Selective ion electrode	A
Sulfate	Gravimetric	A
Nitrogen, Nitrate (as N)	Colorimetric-Brucine	B
Phosphate, Total (as P)	Colorimetric	A
Aluminum	Atomic Absorption-furnace	B
Arsenic	Atomic Absorption-furnace	B
Barium	Inductively coupled plasma	C
Boron	Inductively coupled plasma	C
Calcium	Inductively coupled plasma	C
Cadmium	Atomic Absorption-furnace	B
Chromium	Atomic Absorption-furnace	B
Cobalt	Inductively coupled plasma	C
Copper	Atomic Absorption-furnace	B
Iron	Inductively coupled plasma	C
Lead	Atomic Absorption-furnace	B
Magnesium	Inductively coupled plasma	C
Manganese	Inductively coupled plasma	C
Mercury	Atomic Absorption-cold vapor	B
Molybdenum	Atomic Absorption-furnace	B
Nickel	Inductively coupled plasma	C
Potassium	Atomic Absorption-flame	B
Selenium	Atomic Absorption-furnace	B
Sodium	Atomic Absorption-flame	B
Silver	Atomic Absorption-furnace	B
Vanadium	Inductively coupled plasma	C
Zinc	Inductively coupled plasma	C
Total Uranium	Fluorametric	D
Radium-226	Radon Methods	D

Reference Codes

A = American Public Health Association and others, 1981
B = U.S. EPA, 1979a
C = U.S. EPA, 1979b
D = Health and Safety Regulations, No. 300, 1972

TABLE A-11
LABORATORY WATER QUALITY TEST RESULTS

SAMPLE IDENTIFICATION DATE SAMPLED	WELL B 12-13-82	WELL C 12-14-82	WELL D 12-20-82	POND V 12-20-82	POND W 12-20-82	POND Y 12-19-82	POND Z 12-19-82	SEEP X 12-20-82
MAJOR IONS (mg/l except as noted)								
CALCIUM (Ca)	683.0	619.0	58.9	21.7	157.0	43.3	288.0	349.0
MAGNESIUM (Mg)	284.0	515.0	23.9	8.3	92.8	19.6	175.0	197.0
SODIUM (Na)	1400.0	200.0	1160.0	460.0	360.0	220.0	470.0	340.0
POTASSIUM (K)	23.3	10.7	12.2	5.4	14.0	9.1	9.7	15.9
MANGANESE (Mn)	1.700	.500	.174	< .001	< .001	< .001	5.540	.107
BICARBONATE (HCO3)	99.	244.	835.	442.	193.	82.	108.	329.
CARBONATE (CO3)	< 1.	< 1.	< 1.	< 1.	< 1.	17.	< 1.	< 1.
CHLORIDE (Cl)	24.2	30.7	11.3	17.0	19.0	8.0	17.0	17.0
FLUORIDE (F)	.30	.30	.30	1.20	.80	.60	1.00	.50
SULFATE (SO4)	5560.	3540.	2010.	667.	1380.	540.	2270.	2060.
NITRATE (NO3 as N)	4.8	.8	.3	.8	.4	< .1	1.5	.8
LAB pH (units)	6.43	7.43	7.77	8.34	8.11	8.79	6.92	8.00
CONDUCTIVITY (umhos/cm)	8150.	4430.	4915.	2280.	2760.	1520.	3670.	3670.
TOTAL ALKALINITY (as CaCO3)	80.	200.	685.	363.	158.	67.	89.	270.
TRACE CONSTITUENTS (mg/l except as noted)								
ALUMINUM (Al)	.8	1.1	< .1	< .1	.2	< .1	.3	.4
ARSENIC (As)	.01	< .01	< .01	< .01	< .01	< .01	< .01	< .01
BARIUM (Ba)	< .1	< .1	< .1	< .1	< .1	< .1	< .1	< .1
BORON (Bo)	1.2	.2	.3	.5	.3	.2	.2	.3
CADMIUM (Cd)	.001	< .001	< .001	< .001	< .001	< .001	.002	< .001
TOTAL CHROMIUM (Cr)	.002	.002	.003	< .001	< .001	< .001	< .001	< .001
COBALT (Co)	.18	< .01	< .01	< .01	< .01	< .01	.90	< .01
COPPER (Cu)	.005	.016	< .001	< .001	< .001	< .001	.004	< .001
IRON (Fe)	139.00	.25	.34	.05	< .01	.03	.02	.03
LEAD (Pb)	.004	.002	.002	.001	.001	< .001	.001	< .001
MERCURY (Hg)	< .0004	< .0004	< .0004	< .0004	< .0004	< .0004	< .0004	< .0004
MOLYBDENUM (Mo)	.002	.003	.003	.009	.011	.041	.007	.003
NICKEL (Ni)	.28	< .01	< .01	< .01	< .01	< .01	.20	< .01
TOTAL PHOSPHATE (PO4 as P)	.3	< .1	< .1	< .1	< .1	< .1	< .1	< .1
SELENIUM (Se)	< .01	.02	< .01	< .01	.02	< .01	< .01	< .01
SILICA (SiO2)	25.00	8.60	37.40	11.10	1.50	1.10	5.20	6.20
SIVER (Ag)	< .01	< .01	< .01	< .01	< .01	< .01	< .01	< .01
VANADIUM (V)	.03	< .01	< .01	< .01	< .01	.02	.01	< .01
ZINC (Zn)	.3	< .1	< .1	< .1	< .1	< .1	.2	< .1
URANIUM (U, TOTAL)	.005	1.954	.973	.850	5.965	2.563	2.440	3.520
RADIUM (Ra-226, pCi/l)	11.8	5.5	9.7	9.4	30.9	8.1	12.1	65.1
TOTAL DISSOLVED SOLIDS	8173.	5084.	3788.	1410.	2122.	896.	3256.	3098.
DISSOLVED SOLIDS (sum of major ions)	8265.	5177.	4154.	1641.	2227.	945.	3362.	3324.
TOTAL CATIONS (meq/l)	125.4	82.4	55.7	21.9	31.5	13.6	49.7	48.9
TOTAL ANIONS (meq/l)	118.5	78.7	55.9	21.8	32.5	13.4	49.7	48.9
CHARGE BALANCE (% error)	2.8	2.3	-.2	.4	-1.6	.6	-.0	-.0

* NO ANALYSIS MADE   < BELOW DETECTION LIMIT

TABLE A-12
FIELD WATER QUALITY MEASUREMENTS

Location	Date	Air Temperature (°C)	Water Temperature (°C)	Specific Conductance (umhos/cm)	pH	Eh (mv)	Dissolved* Oxygen (mg/l)	Alkalinity Total (mg/l)	Alkalinity OH (mg/l)	Alkalinity CO_3 (mg/l)	Alkalinity HCO_3 (mg/l)
Well M-1	12/16	7.0	17.5	1600	8.35	-268	0.17	379	-	5.6	450
Well M-2	12/16	2.5	14.7	1800	8.41	-162	1.41	357	-	7.0	421
Well M-3	12/15	4.0	15.5	1800	8.26	-245	0.17	333	-	8.4	389
Well M-4	12/15	4.2	16.0	1600	7.63	-128	0.20	405	-	-	494
Well M-6**	12/18	11.0	16.2	1550	8.08	-247	0.20	384	-	1.8	465
Well M-9	12/16	6.0	16.0	2200	11.59	-119	7.2	381	81.5	85.0	-
Well M-14	12/17	8.0	17.5	670	8.45	-160	1.74	319	-	15.3	358
Well M-16	12/15	9.5	18.5	860	7.73	- 40	5.55	308	-	-	375
Well M-20	12/19	10.0	14.0	2830	7.02	-154	0.84	159	-	-	194
Well M-21	12/17	10.0	16.0	2200	7.73	-230	0.22	437	-	-	533
Well A	12/21	-	-	-	-	-	-	-	-	-	-
Well B**	12/13	0.0	17.0	8600	6.08	+ 40	0.67	156	-	-	191
Well C	12/14	4.0	12.5	4700	6.74	+116	0.37	389	-	-	474
Well D	12/20	8.0	11.0	-	7.74	-106	0.90	887	-	-	1082
Well F	12/21	8.0	14.0	3740	9.61	+ 75	-	-	-	-	-
Pond V S. Paguate Pit	12/20	4.0	5.0	-	8.72	-	9.8	358	-	16.7	403
Pond W N. Paguate Pit	12/20	12.0	6.5	-	8.58	+ 80	9.55	166	-	3.7	195
Seep X N. Paguate Pit	12/20	9.0	14.0	-	7.83	-	8.3	277	-	-	338
Pond Y Jackpile Pit	12/19	4.0	4.0	-	9.65	- 15	12.25	70	-	5.8	74
Pond Z** Jackpile Pit	12/19	10.0	7.2	-	6.85	+140	9.5	111	-	-	136

* All M-series wells had a smell of hydrogen sulfide gas. This and some other gases interfere with DO measurement; therefore, DO measurements are deemed unreliable in M-series wells. Also, cascading water occurred in wells M-9 and M-16.

** Bulk sample locations

TABLE A-13

SURFACE SAMPLE DESCRIPTIONS

Sample No.	Location	Fizz Reaction*	Description
S-1	Pile 4-1	2	Protore - Light gray silty fine sand
S-2	Pile 1-A	1	Protore - Light gray silty fine to coarse sand with some fine gravel
S-3	Pile 2-C	0	Protore - Light gray silty fine sand
S-4	Pile SP-1	1	Protore - Light gray fine gravelly fine to coarse sand with some silt
S-5	S. Paguate Pit 13 area	1	Jackpile Ss Mine Waste - light gray silty fine to medium sand
S-6	N. Paguate Pit, W. side	0	Jackpile Ss Mine Waste - light greenish gray silty fine sand with trace fine gravel
S-7	Jackpile N. side	0	Mixed Dump - Medium gray fine gravelly, silty fine to coarse sand
S-8	Jackpile N. side	0	Jackpile Ss Mine Waste - Light gray silty fine sand
S-9	Pile J-1	0	Protore - Light gray fine gravelly, silty fine to coarse sand
S-10	Pile 6-B	0	Protore - Light gray silty fine sand
S-11	Dump Q	0	Dump-Mancos Shale - Dark gray silty fine sand
S-12	Pile H	1	Mixed Dump - Light greenish gray silty fine to coarse sand with some fine gravel
S-13	Pile J	0	Dump-Jackpile Ss - Light gray fine gravelly, silty fine to coarse sand
DS-1	S. Paguate, N. side	1	Jackpile Ss Mine Waste - Light gray silty fine sand
DS-2	Pile 1-C	0	Protore - Light gray silty fine sand
DS-3	S. Paguate NE. corner	0	Backfill-Dakota Ss and Mancos Shale - Medium gray silty fine sand with some medium to coarse sand and fine gravel
DS-4	S. Paguate SE. corner	1	Jackpile Ss Mine Waste - Light gray silty fine sand
DS-6	Pile SP-1	0	Protore - Light brownish gray fine gravelly fine to coarse sand with some silt
DS-8	S. Paguate SE. corner	0	Backfill-Dakota Ss and Mancos Shale - Dark gray silty fine to coarse sand and fine gravel
DS-9	S. Paguate, south of N. Impoundment	1	Jackpile Ss Mine Waste - Light gray silty fine sand
DM-1	Pile 1-A	0	Protore - Light gray silty fine sand with trace to some clay
DM-2	Pile 2-C	0	Protore - Light gray silty fine sand with trace clay
DM-3	Pile U	0	Mixed Dump - Dark brownish gray silty fine sand with some clay
DM-4	Pile 6-A	0	Protore - Light gray silty fine to medium sand with trace to some clay
DM-5	Pile J	2	Dump-Mixed Materials - Brown silt and fine sand with some clay
DM-6	Jmj, N. Paguate	0	Jackpile Ss - Light greenish gray silty fine to medium sand with trace to some clay
DM-7	Qal, N. Paguate	2	Alluvium - Brown silty fine sand with some clay/cobbles and gravel composed of basalt
DM-8	Pile B-1	0	Protore - Light brownish gray silty fine sand with trace of clay
S-7A	Jackpile N. side	0	Mixed Dump - Dark brownish gray silty fine sand with trace to some clay
S-10A	Pile 6-B	1	Protore - Medium gray silty fine sand with trace clay

*
0 means no reaction to 10% HCI
1 means slight reaction to 10% HCI
2 means strong reaction to 10% HCI

TABLE A-14

MINERALOGY AND CHEMICAL ANALYSES OF SOLID SAMPLES

Sample No.
Location

Sample No. Location	S-2 Protore	S-3 Protore	S-5 Jackpile	S-7 Mixed Dump	S-11 Dump-Mancos	S-12 Mixed Dump
Mineral (Phase Weight Percent)						
Quartz	62.29	66.39	70.42	60.27	36.81	73.31
Feldspar	13.07	18.94	15.82	12.95	12.30	11.53
Kaolinite	10.86	5.34	6.68	8.16	15.53	8.35
Illite	2.58	4.15	3.59	2.22	14.78	3.84
Chlorite	0.30	0.77	0.20	0.20	3.79	0.20
Smectite	3.47	3.97	3.96	14.95	14.63	2.25
Pyrite	0.04	0.03	0.04	0.21	0.56	0.04
Calcite	ND	ND	ND	ND	ND	ND
Rutile	0.18	0.18	0.16	0.45	0.68	0.19

Notes: Quartz represents both quartz and amorphous silica
Smectite represents montmorillonite, nontronite, and saponite
ND means not detected

TABLE A-14 (Cont)

Sample No. Location	S-2 Protore	S-3 Protore	S-5 Jackpile	S-7 Mixed Dump	S-11 Dump-Mancos	S-12 Mixed Dump
Compound (Weight Percent)						
SiO_2	86.19	85.97	87.60	82.05	70.26	88.12
Al_2O_3	7.72	7.09	6.67	8.44	14.12	6.41
Fe_2O_3	1.00	1.23	0.85	2.56	4.04	0.95
TiO_2	0.18	0.18	0.16	0.45	0.68	0.19
CaO	0.18	0.20	0.17	0.90	0.83	0.11
MgO	0.26	0.38	0.25	0.83	2.02	0.19
K_2O	2.17	2.53	2.16	1.74	2.61	2.06
Na_2O	0.18	0.70	0.55	0.43	0.47	0.11
SO_3	0.06	0.04	0.05	0.28	0.75	0.05
MnO	0.00	0.01	0.00	0.02	0.02	0.00
P_2O_5	0.01	0.01	0.00	0.02	0.07	0.01
CO_2	0.00	0.00	0.00	0.00	0.00	0.00
U_3O_8	0.05	0.07	0.01	0.01	0.003	0.03
H_2O+	1.84	1.35	1.31	1.97	4.41	1.51
H_2O-	0.37	0.90	0.43	2.02	3.83	0.40
Organics	0.00	0.00	0.00	0.63	1.68	0.00
Total	99.85	99.75	99.78	99.69	100.26	100.14

Notes: H_2O+ is water driven off by heating sample to 540° and 900°C
H_2O- is water driven off by heating sample to 110°C

TABLE A-15

CATION EXCHANGE CAPACITY AND EXTRACTABLE CATIONS

Sample No.	Description	Extractable Cations (meq/100g)					Cation Exchange Capacity (meq/100g)
		Na +	Ca ++	Mg ++	K +	H +	
S-1	Protore	3.1	8.8	0.6	0.3	0.0	12.8
S-2	Protore	3.5	3.4	1.1	0.3	0.0	8.3
S-3	Protore	3.3	4.0	1.3	0.3	0.0	8.9
S-4	Protore	0.5	3.8	1.9	0.3	3.1	9.6
S-5	Jmj MW	3.2	4.3	1.0	0.5	0.0	9.0
S-7	Mixed Dump	1.0	10.6	5.2	0.3	14.1	31.2
S-7A	Mixed Dump	0.4	4.7	1.7	0.1	9.2	16.1
S-8	Jmj MW	1.3	3.5	1.3	0.3	0.0	6.3
S-9	Protore	0.4	2.7	1.9	0.2	1.1	6.3
S-10	Protore	0.6	2.1	1.6	0.3	3.9	8.4
S-10A	Protore	0.5	2.2	1.0	0.1	3.2	7.1
S-11	Dump-Mancos Shale	3.1	17.1	12.2	0.6	19.9	52.9
S-12	Mixed Dump	2.6	2.6	1.5	0.2	0.0	7.0
S-13	Jmj Dump	0.6	2.9	1.2	0.2	0.0	4.9
DS-1	Jmj MW	2.9	4.2	0.9	0.3	< 0.1	8.3
DS-2	Protore	1.5	3.8	1.1	0.3	< 0.1	6.7
DS-3	Backfill-Kd and Km	0.7	5.2	2.5	0.2	7.6	16.2
DS-4	Jmj MW	5.2	10.5	1.5	0.7	< 0.1	17.9
DS-6	Protore	0.6	4.8	1.8	0.2	4.7	12.1
DS-8	Backfill-Kd and Km	4.0	14.6	4.2	0.5	4.6	27.9
DS-9	Jmj MW	4.2	5.3	1.1	0.4	< 0.1	11.0
DM-1	Protore	1.2	5.4	1.8	0.4	< 0.1	8.8
DM-2	Protore	3.8	4.6	1.2	0.4	< 0.1	10.0
DM-3	Mixed Dump	0.5	10.8	5.0	0.2	14.1	30.6
DM-4	Protore	3.2	2.8	1.8	0.2	< 0.1	8.0
DM-5	Mixed Dump	0.5	38.1	4.2	0.3	< 0.1	43.0
DM-6	Jmj Ss	0.3	3.1	1.7	0.1	7.3	12.5
DM-7	Alluvium	1.1	30.8	7.0	0.4	< 0.1	39.3
DM-8	Protore	1.8	1.9	1.0	0.1	4.9	9.7

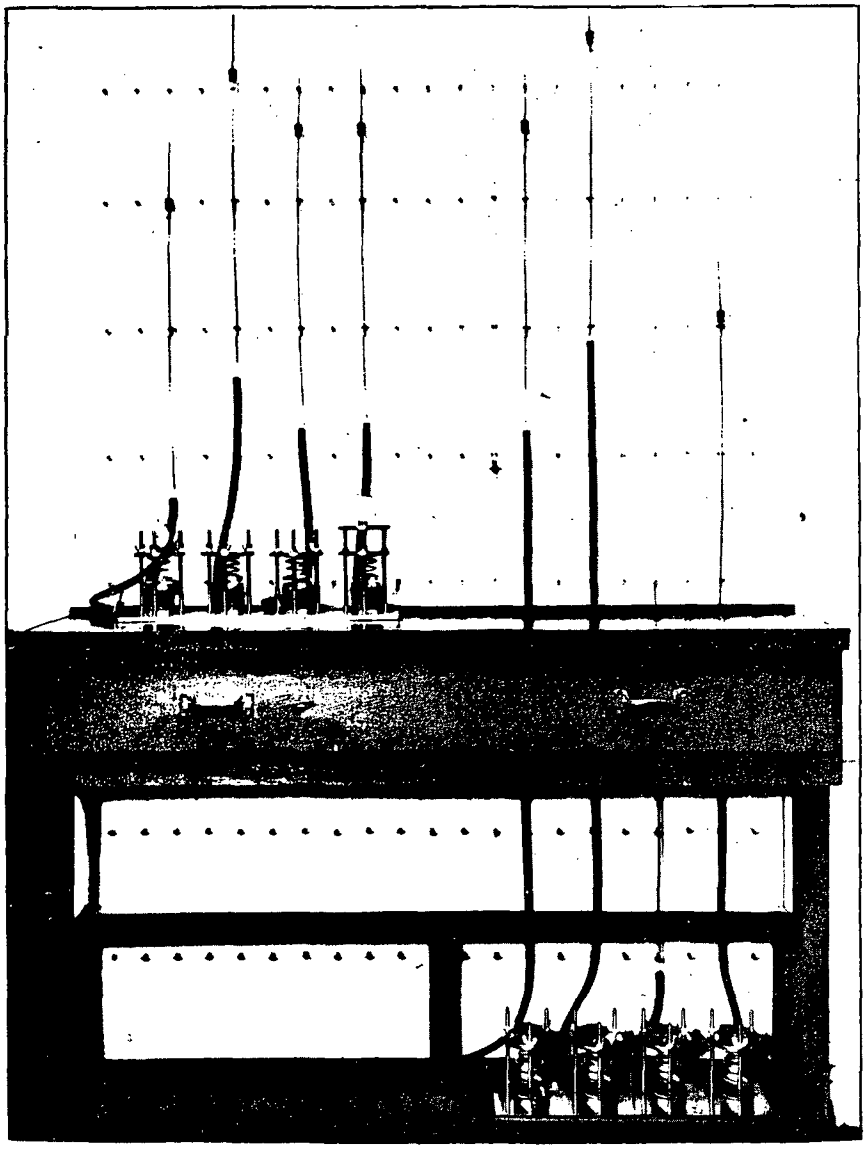
TABLE A-16

SULFUR CONTENT, ACID-BASE POTENTIAL AND pH

Sample No.	Description	Percent Sulfur: Organic	Pyritic	Sulfate	Total	Potentials (tons/1,000 tons $CaCO_3$ equiv.): Acid Potential	Neutralization Potential	Acid-Base Potential	Soil pH
S-1	Protore	< 0.01	< 0.01	0.011	0.011	< 0.1	4.1	4.1	8.8
S-2	Protore	< 0.01	< 0.01	0.024	0.024	< 0.1	1.4	1.4	8.3
S-3	Protore	< 0.01	< 0.01	0.019	0.019	< 0.1	1.4	1.4	8.3
S-4	Protore	< 0.01	< 0.01	0.010	0.010	< 0.1	1.8	1.8	5.3
S-5	Jmj MW	< 0.01	< 0.01	0.110	0.110	< 0.1	1.8	1.8	9.1
S-7	Mixed Dump	0.01	0.21	0.120	0.330	6.6	< 0.1	-6.6	4.7
S-7A	Mixed Dump	0.01	0.20	0.022	0.232	6.3	0.9	-5.4	4.6
S-8	Jmj MW	< 0.01	< 0.01	0.021	0.021	< 0.1	2.8	2.8	8.1
S-9	Protore	< 0.01	< 0.01	0.007	0.007	< 0.1	0.5	0.5	6.4
S-10	Protore	< 0.01	0.02	0.006	0.026	0.6	< 0.1	-0.6	5.3
S-10A	Protore	< 0.01	0.01	0.006	0.106	3.0	0.9	-2.1	5.9
S-11	Dump-Mancos Shale	0.02	< 0.01	0.230	0.250	0.6	< 0.1	-0.6	5.7
S-12	Mixed Dump	< 0.01	< 0.01	0.018	0.018	< 0.1	0.9	0.9	7.5
S-13	Jmj Dump	< 0.01	< 0.01	0.003	0.003	< 0.1	< 0.1	< 0.1	8.6
DS-1	Jmj MW	< 0.01	< 0.01	0.021	0.021	< 0.1	2.1	2.1	8.2
DS-2	Protore	< 0.01	< 0.01	0.013	0.013	< 0.1	0.9	0.9	8.2
DS-3	Backfill-Kd and Km	< 0.01	0.06	0.024	0.024	0.2	< 0.1	-0.2	4.4
DS-4	Jmj MW	< 0.01	< 0.01	0.018	0.018	< 0.1	6.5	6.5	9.2
DS-6	Protore	< 0.01	< 0.01	0.023	0.023	< 0.1	< 0.1	<0.1	5.3
DS-8	Backfill-Kd and Km	0.03	< 0.01	0.021	0.021	0.1	< 0.1	<0.1	6.3
DS-9	Jmj MW	< 0.01	< 0.01	0.023	0.023	< 0.1	0.8	0.8	8.1
DM-1	Protore	< 0.01	< 0.01	0.006	0.006	< 0.1	2.3	2.3	8.0
DM-2	Protore	< 0.01	< 0.01	0.010	0.010	< 0.1	1.8	1.8	8.9
DM-3	Mixed Dump	0.02	0.20	0.027	0.247	6.6	1.4	-5.2	4.8
DM-4	Protore	< 0.01	< 0.01	0.018	0.018	< 0.1	1.8	1.8	7.3
DM-5	Mixed Dump	0.01	< 0.01	0.020	0.030	0.3	32.7	32.4	8.0
DM-6	Jmj Ss	< 0.01	0.20	0.026	0.226	6.0	< 0.1	-6.0	4.1
DM-7	Alluvium	0.02	< 0.01	0.021	0.041	0.6	30.8	30.2	8.0
DM-8	Protore	< 0.01	0.01	0.023	0.123	3.0	1.8	-1.2	5.6

The quantity and the velocity of flow of water which will escape through an earth structure or percolate through soil are dependent upon the permeability of the earth structure or soil. The permeability of soil has often been calculated by empirical formulas but is best determined by laboratory tests, especially in the case of compacted soils.

A one-inch length of the core sample is sealed in the percolation apparatus, placed under a confining load, or surcharge pressure, and subjected to the pressure of a known head of water. The percolation rate is computed from the measurements of the volume of water which flows through the sample in a series of time intervals. These rates are usually expressed as the velocity of flow in feet per year under a hydraulic gradient of one and at a temperature of 20 degrees Centigrade. The rate so expressed may be adjusted for any set of conditions involving the same soil by employing established physical laws. Generally, the percolation rate varies over a wide range at the beginning of the test and gradually approaches equilibrium as the test progresses.



APPARATUS FOR PERFORMING PERCOLATIONS TESTS
Shows tests in progress on eight samples simultaneously.

During the performance of the test, continuous readings of the deflection of the sample are taken by means of micrometer dial gauges. The amount of compression or expansion, expressed as a percentage of the original length of the sample, is a valuable indication of the compression of the soil which will occur under the action of load or the expansion of the soil as saturation takes place.

METHOD OF PERFORMING PERCOLATION TESTS

DAMES & MOORE

APPENDIX B

APPENDIX B

MATHEMATICAL MODEL DOCUMENTATION

1.0 INTRODUCTION

The purpose of this appendix is to present a description of a comprehensive mathematical model for the prediction of momentum, heat and mass transfers in porous media. This presentation is prefaced by a review of recently published literature concerning prediction procedures for flows in porous media coupled with heat and/or mass transfers. Sub-surface porous media are the primary subjects of concern here, and the review is intended to provide an overview of the state-of-the-art. For this reason, it is necessarily brief.

The prediction procedures for the mechanisms considered here include analytical solution techniques for simplified governing equations as well as mathematical models based upon numerical solution techniques for sets of coupled and uncoupled governing differential equations. Attempts have not been made to prepare here a detailed classification of these procedures based upon rigorous mathematical criteria. The intention rather is to present a coherent summary which highlights the salient features of, and recent advances made in, prediction procedures.

It is recognized that in preparing this review complete attention may not have been paid to the degree of validation, in respect of reliable field and laboratory data, that each available procedure may have been subjected to. The levels of sophistication and flexibility built into the procedures which permit them to accept such data in some convenient form, will be considered sufficient for the purposes of this review. This is largely due to the paucity of data, in sufficient quantity and of suitable quality, readily available for purposes of validation.

In the following sub-sections, reviews are separately presented for hydrodynamic aspects, aspects of chemical-species transport, and heat-transfer aspects respectively. This loose sub-division is maintained purely for reasons of convenience in presentation.

1.1 HYDRODYNAMICS

Analytical techniques for solving simplified equations of ground-water mass balance have been employed now for a number of years. These techniques involve basic assumptions about the geometric configuration of the flow domain, eg. water-table aquifer, leaky bed, etc., and the uniformity of material properties. The employment of these techniques usually results in closed-form expressions for hydraulic head as a function of space and time. The velocity fields are then extracted by the appropriate use of Darcy's law, which has been incorporated into the mass balance equation employing hydraulic head as the dependent variable.

The deployment of a useful analytical technique for the flow distribution in multiple inter-connected aquifers has been reported by Bredehoeft and Pinder (1970). A recent and elegant treatment of the so-called leakage flow between aquifers is presented by Dever and Cleary (1979). The principal assumption involved in the above procedures is that the flow field in each aquifer is entirely saturated and two-dimensional. Analytical solutions to the more difficult problem of unsaturated-flows under similar conditions has received relatively little quantitative attention. Braester et al. (1971) have prepared a comprehensive survey of governing equations for unsaturated flows. Gambolati (1973) has presented a discussion of vertical unsaturated flow analyses. It may be concluded, however, that versatile analytical procedures for saturated/unsaturated flow predictions do not, in general, exist. A simple one-dimensional semi-empirical procedure for predicting purely unsaturated flows has, however, recently been reported by McWhorter and Nelson (1979) who applied it to the prediction of seepage beneath uranium tailings ponds.

Recent years have seen the proliferation of mathematical models based upon numerical schemes for solving the non-linear form of the mass-conservation equation. Narasimhan and Witherspoon (1977) review much of the current literature on the subject and indicate that both finite-difference and finite-element techniques have been employed with varying degrees of success. The premier ones of the former variety are those developed by Bredehoeft and Pinder (1970), Prickett and Lonnquist (1971), Cooley (1974), Trescott et al. (1976), and Sharma (1979). Of the latter variety, the works by Narasimhan (1975), Neuman (1973) and Pinder (1973) represent the principal ones. Trescott and Larson (1977), in a series of numerical experiments, compare the efficacy of iterative methods used to solve sets of algebraic equations resulting from arbitrary forms of numerical discretization.

Numerical procedures particularly suited to the prediction of saturated/unsaturated flows have also been developed (see for example Freeze, 1971; Narasimhan et al., 1977; Sharma and Hamilton, 1978; etc). The numerical formulation of leakage interactions between elements of a multiple aquifer system are extensively discussed by Frind (1979). The numerical simulation of individual wells of arbitrary size as well as the interactions amongst them have been reported by Prickett and Lonnquist (1971) and Akbar et al. (1974).

An assessment of these and other similar procedures, in formulation and especially in implementation to practical circumstances, has been prepared recently by Weston (1978). In agreement with this assessment, it is argued here that numerical procedures, of sufficient degrees of comprehensiveness are presently available for application to the range of problems currently encountered. The major areas of weakness in such applications are: the prediction of flows in porous media with superposed fracture distributions; and, the supply of adequate amounts of reliable data to calibrate the procedures. The state-of-the-prediction art for flows in fractured media has been thoroughly reviewed recently by Gringarten (1979).

1.2 MASS TRANSFER

The use of the term mass transfer here is intended to signify the transport of inert and/or reacting chemical species within porous media by the complex interaction of several physical and chemical mechanisms. The set of such mechanisms, loosely termed as sorption in the literature, considered here as a basis for review is:

- convection;
- diffusion and dispersion;
- cation-exchange reactions;
- mechanical filtration;
- buffering of pH;
- chemical precipitation by reactions with the solid matrix as well as the interstitial water;
- hydrolysis and precipitation;
- oxidation-reduction reactions;
- radioactive decay;
- volatilization; and,
- biological degradation;

It must be emphasized that specialized knowledge of the in-situ effects of individual mechanisms are, at present, understood only to a limited extent. The set of sophisticated measurements necessary to quantify these influences for each geological medium and chemical specie are currently being made in a variety of contexts. It is thus reasonable to suppose that the data obtained from these measurements will be available within a few years for purposes of refining the available mathematical models.

Analytical solutions to the convective dispersion equation have been developed by a number of authors, each of whom has been interested in specific geometric configurations and specific chemical species. The deployment of these solutions has been governed to a large extent by the requirements of the technical discipline within which each problem has been tackled. For instance, a one-dimensional solution including adsorption effects has been developed by Gupta and Greenkorn (1973) as a tool in soil-chemistry. The work by Aikens et al. (1979), on the other hand, presents a variety of useful analytical solutions which take radioactive decay into account. Such solutions are indeed simple to use, and provide order-of-magnitude results in respect of concentration distributions with a modicum of effort. However, as geometries, material properties or the reactive mechanisms themselves become more complex, it is more convenient to employ mathematical models based upon numerical solution techniques.

One-dimensional models of this type abound in the literature. An interesting work by Selim et al. (1977) is concerned with finite-difference simulations of reactive solute transport through multilayered soils. Davidson et al. (1978) report the extension of this work to the finite-difference treatment of coupled adsorption, convective dispersion as well as biological degradation. This work represents an excellent study of the effects of pesticides in soils. The recent publication by Konikow and Bredehoeft (1978) describes a two-part finite-difference procedure for solving the coupled flow and chemical-species transport equations. A comprehensive, coupled procedure, employing a sophisticated hybrid differencing scheme, has also been developed by Sharma (1981). These procedures are typical of several available schemes, of varying degrees of computational economy, being currently reported. To be entirely valid each such procedure must be supplied with reliable physical and chemical data, appropriate to a given application.

In like fashion, finite-element based numerical methods have been developed by researchers for predicting chemical-species transport in porous media. Rubin and James (1973) present one such method which uses the Galerkin approach. Duguid and Reeves (1976) document another similar method which has had numerous practical applications. Gray and Pinder (1976) discuss the efficacy of this and other finite-element approaches, and in addition compare their relative accuracies. The application of one such finite-element approach by Pinder (1973) to groundwater contamination in Long Island is a meticulously-documented study augmented by field measurements. The application of finite-element methods to other types of problems involving transport of chemical species has also been achieved. A good example of such an application by Kealy et al. (1974) involves the analysis of seepage from tailings ponds. It is in this connection that the work by Duguid and Reeves (1976) is well known. Weston (1978) presents a comprehensive review of currently available models of the above types and, based upon their degree of validation and use, commends some for routine application. In short, a wide range of models covering a range of applicability is presently available for use in predicting the transport of reacting chemical species. The data requirements for these models are not always met to the same level of quality.

1.3 HEAT TRANSFER

The analysis of heat transfer coupled with fluid flow in porous media, has also been conducted using both analytical and numerical techniques. The analytical solutions, depending on specific boundary conditions which are implicitly incorporated into them, have much in common with those for transport of chemical species. However, the range of application of both analytical and numerical solutions for heat transfer is limited when compared with transport of chemical species. The limitation is primarily due to the recent nature of public interest in energy applications in underground media.

The work by Harlan (1973) on the prediction of freezing in soils is an excellent early example of the use of a numerical procedure for the analysis of freezing fronts in porous media. Likewise, Holst and Aziz (1972) as well as Rubin and Roth (1979) examine aspects of thermally-induced convection in porous media and the stability of such flows. The former authors present a detailed investigation of three-dimensional flows. Special attention has been paid by Runchal et al. (1978) to the problem of heat-transfer effects, resulting from the disposal of high-level radioactive waste, upon groundwater motion. They treated this phenomenon as essentially decoupled. All such procedures depend, of course, on the supply of adequate field data, of sufficient quantities and of sufficient quality for purposes of input and validation. Such data, in respect of heat transfer, is extremely sparse, and hence most heat transfer models must be considered to be in a state of development. A recent example of field measurements of temperature effects in porous-media flows is that by Molz et al (1978). These measurements were specifically made in connection with thermal energy storage in aquifers. The problems involved in such storage have been discussed by Werner and

Kley (1977). Theoretical studies of this problem, using both finite-difference and finite-element methods have been reported. Amongst the former is the work by INTERCOMP (1976); examples of the latter are: Mercer et al (1975); and, Papadopulos and Larson (1978)

2.0 MATHEMATICAL FOUNDATIONS

2.1 PREAMBLE

In what follows, a mathematical description is provided of a general version of the computational procedure embodied in a computer program collectively termed "the model." Two-dimensional versions of the model have been sucessfully employed in a variety of engineering applications. A simple three-dimensional version of the model has also been developed, tested and applied recently by Dames & Moore (Sharma, 1981; and Hamilton and Sharma, 1981). The procedure is economical of computational effort, whilst retaining the sophistry of physical and chemical formulations, embedded in other models mentioned above, and maintains mass conservation to desired levels at each time instant of interest.

2.2 GOVERNING EQUATIONS

The symbols in the following equations are described in the nomenclature list. Their derivation has been documented extensively elsewhere.

a. Mass Conservation

It can be shown (Bear, 1972) that the primitive form of the continuity equation can be combined with the generalized definition of Darcy velocity to yield the partial differential equation governing flow, with piezometric head as the dependent variable. Expressed in general two-dimensional form, principally for convenience of understanding, this equation is:

$$S_c \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \{\Gamma_x^h \frac{\partial h}{\partial x}\} + \frac{\partial}{\partial y} \{\Gamma_y^h \frac{\partial h}{\partial y}\} + S^h \tag{1}$$

Specific forms of this general equation are outlined below. The coordinate directions used in these forms imply that y is used interchangeably for one horizontal or the vertical coordinate direction. For <u>vertical plane</u> flows (y-positive upwards), the following definitions apply:

$$\begin{aligned}
\Gamma_x^h &\equiv K_{xx}M \\
\Gamma_y^h &\equiv K_{yy}M \\
S^h &\equiv - \frac{\partial}{\partial y} (K_{yy}MR) + \dot{q}''' \\
M &\equiv \frac{\mu_o}{\mu} \\
R &\equiv 1 - \frac{\rho}{\rho_o}
\end{aligned} \tag{2}$$

For <u>horizontal-plane</u> flows under <u>confined</u> conditions the following definitions apply:

$$\begin{aligned}
\Gamma_x^h &\equiv K_{xx}M\ S_t \\
\Gamma_y^h &\equiv K_{yy}M\ S_t \\
S^h &\equiv \dot{q}'' \\
M &\equiv \frac{\mu_o}{\mu} \quad \text{and} \quad R = 0
\end{aligned} \tag{3}$$

For horizontal-plane flows under unconfined conditions with M and R defined as in (3) the following definitions apply:

$$\begin{aligned} \Gamma_x^h &\equiv K_{xx} M\, h \\ \Gamma_y^h &\equiv K_{yy} M\, h \\ S^h &\equiv \dot{q}'' \end{aligned} \tag{4}$$

b. Fluid Velocity Components

The well-known Darcy hypothesis is used to relate the velocity components to the distributions of total head, h.

$$\begin{aligned} h &\equiv \frac{p}{\rho_o g} + z \\ n\, U &\equiv - K_{xx} M \frac{\partial h}{\partial x} \\ n\, V &\equiv - K_{yy} M \frac{\partial h}{\partial y} + K_{yy} M\, R \end{aligned} \tag{5}$$

c. Chemical Species Conservation

It has been shown (Sharma, 1981) that the two-dimensional form of the general convective transport equation for the conservation of chemical species, j is:

$$\begin{aligned} &\frac{\partial}{\partial t} (n\rho C_j) + \frac{\partial}{\partial t} \{[1 - n]\rho_s C_{s,j}\} + \frac{\partial}{\partial x} \{n\rho U C_j\} + \frac{\partial}{\partial y} \{n\rho V C_j\} \\ &= \frac{\partial}{\partial x} \{n\rho D_{x,j} \frac{\partial C_j}{\partial x}\} + \frac{\partial}{\partial y} \{n\rho D_{y,j} \frac{\partial C_j}{\partial y}\} + S^{C_j} \end{aligned} \tag{6}$$

d. <u>Thermal Energy Conservation</u>

Likewise the conservation of thermal energy is:

$$\frac{\partial}{\partial t}(n\rho C_V T) + \frac{\partial}{\partial t}\{[1-n]\rho_s C_{v,s} T_s\} + \frac{\partial}{\partial x}\{n\rho U C_P T\} + \frac{\partial}{\partial y}\{n\rho V C_P T\}$$

$$= \frac{\partial}{\partial x}\{nK_{x,T}\frac{\partial T}{\partial x}\} + \frac{\partial}{\partial y}\{nK_{y,T}\frac{\partial T}{\partial y}\} + S^T \qquad (7)$$

The source terms S^{C_j} and S^T in equations (6) and (7) account for supply and/or annihilation of the respective variables due both to natural and man-made events.

2.3 INITIAL AND BOUNDARY CONDITIONS

Initial and boundary conditions, respectively within and on the boundary of the solution domain, must be supplied for each of the dependent variables in order to complete the mathematical specification of the problem.

Initial conditions designate the distribution of h, C_j and T, over the entire solution domain of interest, at the commencement of the solution. Such conditions may be obtained from the results of a field-measurement program and extrapolations thereof, as for example would be the regional piezometric head distribution. Alternatively, they may be obtained from laboratory-scale experiments, as for example the ambient concentration of chemical species in ground water. They may also be supplied from the results of previous calculations of a similar nature.

Boundary conditions represent variations of the dependent variables, their fluxes or combinations thereof, at the boundaries of the solution domain. Such conditions may also be obtained from the results of a field-measurement program, as would be the case, for instance, with recharge boundaries. It is important to note that boundary conditions may vary with time. As a result, they influence the accuracy of results obtained with, and hence the numerical algorithms embodied in, computational solution procedures.

In addition to the above it must be noted that certain man-made as well as natural influences affect the distribution of h, C_j and T within the solution domain. Such influences include discharging (and/or recharging) wells; artifical and natural barriers to flow (as well as heat and mass transfer) occurring locally within the domain. It may be noted at this point that significant advantages accrue from a comprehensive mathematical formulation such as that outlined above. The advantages, principally in respect of flexibility in model applications to a large variety of problems, can be maintained only if the numerical algorithm selected for solution of the equations exhibits equally versatile features. Just such as algorithm is described below.

3.0 NUMERICAL SOLUTION PROCEDURE

3.1 GENERAL

The numerical procedure adopted in the present model, in its one-, two- or three-dimensional versions, is of the integrated finite-difference (IFD) variety. The origins of this procedure lie in an earlier work on computational fluid mechanics and heat transfer (Sharma, 1974). Details of the present procedure are available in Sharma (1981). A brief description is provided in this section.

3.2 NUMERICAL GRID AND VARIABLE LOCATIONS

An illustration of the numerical grid adopted in the x-y plane is illustrated in Figure (1). In this figure the faces of control volumes, used in deriving the discretised equations, are indicated as dashed lines. The intersections of grid lines, which are termed grid nodes, are chosen to lie at the geometric center of the associated control volumes. An exception is made at the boundaries of the domain where the modes lie on the boundaries themselves.

All problem variables, with the exception of the velocity components U and V, are presumed to be located at grid nodes. The x-direction velocity components U are presumed to lie on the intersections of the control-volume faces in the y-direction with the x-direction grid lines. Likewise, the y-direction velocity components V are presumed to lie on the intersections of the control-volume faces in the x-direction with y-direction grid lines. In general, with the possibility of using variable grid spacings in any given direction, it is important to note that velocity components in any given direction do not lie exactly midway between grid nodes in that direction. This feature influences the numerical algorithm in a significant way.

3.3 THE DISCRETISED EQUATIONS

Discretised forms of the partial-differential equations (1), (6), and (7) are obtained by integrating them over the above-mentioned control volumes. It is presumed for purposes of this integration that the dependent variables vary linearly between successive grid nodes. Furthermore, one such discretised algebraic equation, per dependent variable, may be derived in this manner for each control volume within the solution domain. It is precisely such an algebraic equation which represents, in finite-difference form, the conservation of mass, thermal energy or of chemical species. The preservation of these conservation principles in the simultaneous solution of the algebraic equations permits, in the present procedure, an exact accounting of mass, energy, and momentum to be made. It is of great importance to note that such precise accounting of chemical species is vital in problems concern with the limited disposal of waste at a given site. Many, otherwise praiseworthy mathematical models, do not ensure that this is the case.

The discretised equations, at an arbitrary grid node P with its neighbors at E, W, N and S, have the following forms:

a. Piezometric head:

$$\left(\sum_{P} A^{h} - SN_{p}^{h}\right) h_{p} = \sum_{i=E,W,N,S,O} A_{i}^{h} h_{i} + SO_{p}^{h} \tag{8}$$

b. Species concentration:

$$\left(\sum_{P} A^{C_j} - SN_{P}^{C_j}\right) C_{j,P} = \sum_{i=E,W,N,S,O} A_{i}^{C_j} C_{j,i} + SO_{P}^{C_j} \tag{9}$$

c. Temperature:

$$\left(\sum_{P} A^{T} - SN_{P}^{T}\right) T_{P} = \sum_{i=E,W,N,S,O} A_{i}^{T} T_{i} + SO_{P}^{T} \tag{10}$$

In the above, A's denote coefficients computed from known (or sometimes temporarily presumed known) values of hydraulic conductivity, dispersion coefficients etc.; and SO, SN are components of a linearised source term; i denotes respectively the neighbouring grid nodes in space; and, O denotes the coefficient associated with the previous-time value of the appropriate dependent variable.

3.4 THE SOLUTION ALGORITHM

The sets of simultaneous algebraic equations noted above are solved by the efficient application of an alternating-direction, heavily-implicit, line-by-line solution algorithm coupled, for three-dimensional problems, to a plane-by-plane block correction procedure. Details are provided by Sharma (1981). This algorithm applied iteratively leads to relatively monotonic solutions for most problems with commonly-encountered boundary conditions.

Brief details of computer programs which enbody the above described numerical procedure are provided below.

4.0 COMPUTER-PROGRAM DETAILS

The algorithm mentioned above has been incorporated into a set of computer programs written for one-, two- and three- dimensional problems. In the program a serious attempt has been made to preserve the flexibility of the mathematical and of the numerical solution procedure. In keeping with this objective, the main machinery of the calculation procedure is kept entirely separate from the problem-specific and user-modifiable portions of the programs. Thus, they are versatile and relatively easy to employ. These programs, called TARGET-S (for Transient Analyser of Reacting Ground Water Effluent Transport in Saturated porous media), are written in standard FORTRAN-IV. They are thus capable of being run on most available computers. On a CDC-6600 machine a typical computer run for an unsteady two-dimensional problem requires approximately 60 seconds of central processor time.

5.0 SOME PREDICTED RESULTS

For purposes ot testing the computer program TARGET-S and to demonstrate the accuracy of results predicted thereby, a few test runs were first made of a selected problem. The problem posed is that of unsteady convective dispersion in a homogeneous, saturated porous medium in one space dimension.

Grid-dependency tests were first conducted to determine the effect of grid-size upon numerical accuracy. It was observed that sufficiently accurate results may be obtained with a number of grid nodes which is also compatible with reasonable computing effort. Further tests investigating the dependence of accuracy upon the chosen time-step were conducted. The results of these are illustrated in Figures 2 and 3, which indicate that for desired levels of accuracy a sufficiently small time-step must be chosen. Subsequently predictions of concentrations of a moving solute front were made. For a given set of parameters, the predicted results for this case may be observed in Figure 3 to compare very favourably with the corresponding exact analytical solution.

TARGET-S has undergone numerous other tests, not reported here, to ensure that the program is essentially correct and that the results predicted with it are both plausible and valid. The validation tests are continuing.

The application of TARGET-S to a few representative problems is illustrated in Figures 4 to 8. In Figure 4, plots of piezometric head at successive time instants illustrates the achievement of steady-state leakage from a river to an underlying aquifer due to a continuously-operating pumping well. Figure 5 illustrates the performance of a set of dewatering wells employed to reduce pressures around an open pit mine. Figures 6 and 7 illustrate, via piezometric heads and corresponding velocity vectors respectively, the effect of a slurry wall in preventing flow to a chemically-contaminated portion of an aquifer. Figures 8a, 8b and 8c illustrate the transient nature of chemical specie transport from an in-pit disposal system for wastes from a lignite-gasification facility. In addition to the above applications, TARGET-S is currently being applied to problems of radioactive and toxic waste disposal alternatives.

6.0 REFERENCES

Aikens, A.E., Jr., R.E. Berlin, J. Clancy, and O.I. Oztunali (1979) "Generic methodology for assessment of radiation does from ground-water migration of radionuclides in LWR wastes in shallow land burial trenches." Dames & Moore report prepared for the Atomic Industrial Forum, Inc.

Akbar, A.M., M.E. Arnold and O.H. Harvey (1974) "Numerical simulation of individual wells in a field simulation model" Soc. Pet. Eng. J., pp 315-320.

Bear, J. (1972) "Dynamics of fluids in porous media," American Elsevier, New York.

Braester, C., G. Dagan, S. Newman and D. Zaslavsky (1971) "A survey of the equations and solutions of unsaturated flow in porous media." Ann. Rep. 1, Proj. A 10-SWC-77, Israel Institute of Technology, Haifa, 176 p.

Bredehoeft, J.D. and G.F. Pinder (1970) "Digital analysis of areal flow in multi-aquifer ground water systems: a quasi three-dimensional model" Water Resources Res., 6, (30), pp 883-888.

Cooley, R.L. (1974) "Finite-element solutions for the equations of ground water flow" Des. Res. Inst., Univ. of Nevada, Tech Rep. Series H-W, Pub. No. 18, 134 p.

Davidson, J.M., L-T Ou, and P.S.C. Rao (1978) "Adsorption, movement and biological degradation of high concentrations of selected pesticides in soils." Proc. 4th Annual Res. Symp. on Land Disposal of Hazardous Wastes, pp. 233-244.

Dever, R.J. and R.W. Cleary (1979) "Unsteady-state, two-dimensional response of leaky aquifers to stream stage fluctuations" Adv. Water Resource. 2, (1), pp 13-18.

Duquid, J. O. and M. Reeves (1976) "Material transport through porous media: A finite-element Galerkin model." Oak Ridge National Laboratory ORNL-4928.

Freeze, R.A. (1971) "Three-dimensional, transient, saturated-unsaturated flow in a ground water system." Water Resources Res., 7, (2), pp 347-366.

Frind, E.O. (1979) "Exact aquitard response functions for multiple aquifer mechanics" Adv. Water Resource., 2, (2), pp 77-82.

Gambolati, G. (1973) "Equation for one-dimensional vertical flow of ground water: 1, the rigorous theory" Water Resources Res., 9, (4), pp 1022-1028.

Gray, W.G. and G.F. Pinder (1976) "An analysis of the numerical solution of the transport equation." Water Resources Res., 12(3), pp. 547-555.

Gringarten, A. C. (1979) "Flow test evaluation of fractured reservoirs." Presented at the symposium on "Recent Trends in Hydrology" Berkeley, Calif. Feb 8-9.

Gupta, S.P. and R.A. Greenkorn (1973) "Dispersion during flow in porous media with bilinear adsorption." Water Resources Res., 9(5), pp. 1357-1368.

Hamilton J.L. and D. Sharma (1981) "Applications of a comprehensive mathematical model (TARGET) capable of predicting flow and chemical-species transport in porous media." Dames & Moore Advanced Technology Group report under preparation.

Harlan, R.L. (1973) "Analysis of coupled heat-fluid transport in partially frozen soil." Water Resources Res., 9(5), pp. 1314-1323.

Holst, P.H. and Aziz, K. (1972) "Transient three-dimensional natural convection in confined porous media." Int. J. Heat and Mass Transfer, 15, pp 73-88.

INTERCOMP Resources Development and Engineering, Inc. (1976) "A model for calculating effects of liquid waste disposal in deep saline aquifers." U.S. Geol. Surv. Water Res. Invest., pp. 76-61.

Kealy, C.D., R.A. Busch and M.M. McDonald (1976) "Seepage - environmental analysis of the slime zone of a tailings pond." U.S. Bureau of Mines, Rep. 7939, 89p.

Konikow, L.F. and J.D. Bredehoeft (1978) "Computer model of two-dimensional solute transport and dispersion in ground water" U.S.G.S., Techniques of Water Resource Investigations, book 7, ch. c2.

McWhorter, D.B. and J.D. Nelson (1979) "Unsaturated flow beneath tailings impoundments." Paper submitted to ASCE Journal of Geotechnical Engineering Development, 32p.

Mercer, J. W., G. F. Pinder, and I. G. Donaldson (1975) "A Galerkin finite element analysis fo hydrothermal system at Wairakei, New Zealand," J. Geophys. Res., 80, pp. 2608-2621.

Molz, F. J., J. C. Warman and T. E. Jones (1978) "Aquifer storage of heated water: Part I - A field experiment." Ground Water, 16, pp. 234-241.

Narasimhan, T.N. (1975) A unified numerical model for saturated-unsaturated ground water flow. Ph. D. dissertation, Univ. of California, Berkeley, California.

Narasimhan, T.N. and P.A. Witherspoon (1977) "Recent developments in modelling ground water systems." Rep. LBL-5209, Lawrence Berkeley Laboratory , University of California, Berkeley, California.

Neuman, S.P. (1973) "Saturated-unsaturated seepage by finite elements." Journ. Hydr. Div. ASCE, 99 (HY12), 2233-2250.

Papadopulos, S. S., and S. P. Larson (1978) "Aquifer storage of heated water: Pat II - Numerical simulation of field results." Ground Water 16, pp. 242-248.

Pinder, G.F. (1973) "A Galerkin - finite element simulation of ground water contamination on Long Island, New York." Water Resources Res., 9(6), pp. 1657-1669.

Prickett, T.A. and C.G. Lonnquist (1971) "Selected digital computer techniques for ground water resource evaluation". Illinois State Water Survey, Bull. 55, 62 p.

Rubin, H. and C. Roth (1979) "On the growth of instabilities in ground water due to temperature and salinity gradients" Adv. Water Resources, 2, (2), pp 69-76.

Rubin J. and R.V. James (1973) "Dispersion-affected transport of reacting solutes in saturated porous media: Galerkin method applied to equilibrium-controlled exchange in uni-directional steady water flow." Waqter Resources Res., 9(5), pp. 1332-1256.

Runchal, A.K., J. Treger and G.S. Segal (1978) "Two-dimensional coupled thermal and fluid-flow analysis in porous media" Dames & Moore, Advanced Tech. Group Rep. TN-LA-34.

Selim, H.M., J.M. Davidson and P.S.C. Rao (1977) "Transport of reactive solutes through multi-layered soils." Soil. Sci. Soc. of Amer. J., 41(1), pp. 3-10.

Sharma, D. (1974) "Turbulent convective phenomena in straight rectangular-sectioned diffusers." Ph.D. Thesis, Imperial College, London, U.K.

Sharma, D. and J.L. Hamilton (1978) "A comprehensive mathematical model for the prediction of saturated-unsaturated flow in porous media." Dames & Moore Advanced Technology Group Report No. TN-LN-DN-14.

Sharma, D. (1981) "A comprehensive mathematical model capable of predicting flow and heat transfer as well as chemical-species transport in porous media." Dames & Moore, Advanced Tech. Group Rep. TN-DN-42.

Trescott, P.C., G.F. Pinder and S.P. Larson (1976) "Finite-difference model for aquifer simulations in two dimensions with results of numerical experiments" U.S.G.S., Tech. of Water Resource Investigations, Book 7, Ch. cl.

Trescott P.C. and S.P. Larson (1977) "Comparison of iterative methods of solving two-dimensional groundwater flow equations." Water Resource Res., 13(1), pp. 125-135.

Werner, O., and W. Kley (1977) "Problems of heat storage in aquifers." J. Hydrol., 34, pp. 37-43.

Weston, R.F. (1978) "Pollution prediction techniques for waste disposal siting: a state-of-the-art assessment." Rep. prepared for office of solid waste hazardous waste management division, U.S.E.P.A.

7.0 NOMENCLATURE

A_i^ϕ	Coefficients representing hydraulic conductivity or dispersion coefficients etc., for variable ϕ at grid position i
C_j	Chemical species concentration of species j ($kg.m^{-3}$)
C_p	Specific heat capacity at constant pressure ($J.kg^{-1}.{}^oC^{-1}$)
C_v	Specific heat capacity at constant volume ($J.kg^{-1}.{}^oC^{-1}$)
$C_{v,s}$	Specific heat capacity of the solid at constant volume ($J.kg^{-1}.{}^oC^{-1}$)
$D_{x,j}$	Dispersion coefficient for species j in x-direction ($m^2.s^{-1}$)
$D_{y,j}$	Dispersion coefficient for species j in y-direction ($m^2.s^{-1}$)
h	Hydraulic or piezometric head (m)
K_{xx}	x-direction hydraulic conductivity ($m.s^{-1}$)
K_{yy}	y-direction hydraulic conductivity ($m.s^{-1}$)
$K_{x,T}$	x-direction thermal conductivity ($J.s^{-1}.m^{-1}.{}^oC^{-1}$)
$K_{y,T}$	y-direction thermal conductivity ($J.s^{-1}.m^{-1}.{}^oC^{-1}$)
M	Viscosity ratio
n	Porosity
$\dot{q}'''$	Point source of mass ($m^3.s^{-1}.m^{-3}$)
R	Density ratio deficit
S_c	Storage coefficient (m^{-1})
S_t	Saturated thickness (m)
S^ϕ	Source term for variable ϕ
SO_P^ϕ	Component of linearized source term for variable ϕ at node P
SN_P^ϕ	Component of linearized source term for variable ϕ at node P

T	Temperature (^oC)
t	Time (s)
U	x-direction velocity ($m.s^{-1}$)
V	y-direction velocity ($m.s^{-1}$)
x,y,z	Cartesian coordinate directions (m)
μ	Viscosity ($kg.m^{-1}.s^{-1}$)
μ_o	Reference viscosity ($kg.m^{-1}.s^{-1}$)
Γ_x^ϕ	Effective diffusion coefficient for variable ϕ, in direction x
ρ	Density ($kg.m^{-3}$)
ρ_o	Reference density ($kg.m^{-3}$)

SCHEMATIC ILLUSTRATION OF NUMERICAL GRID

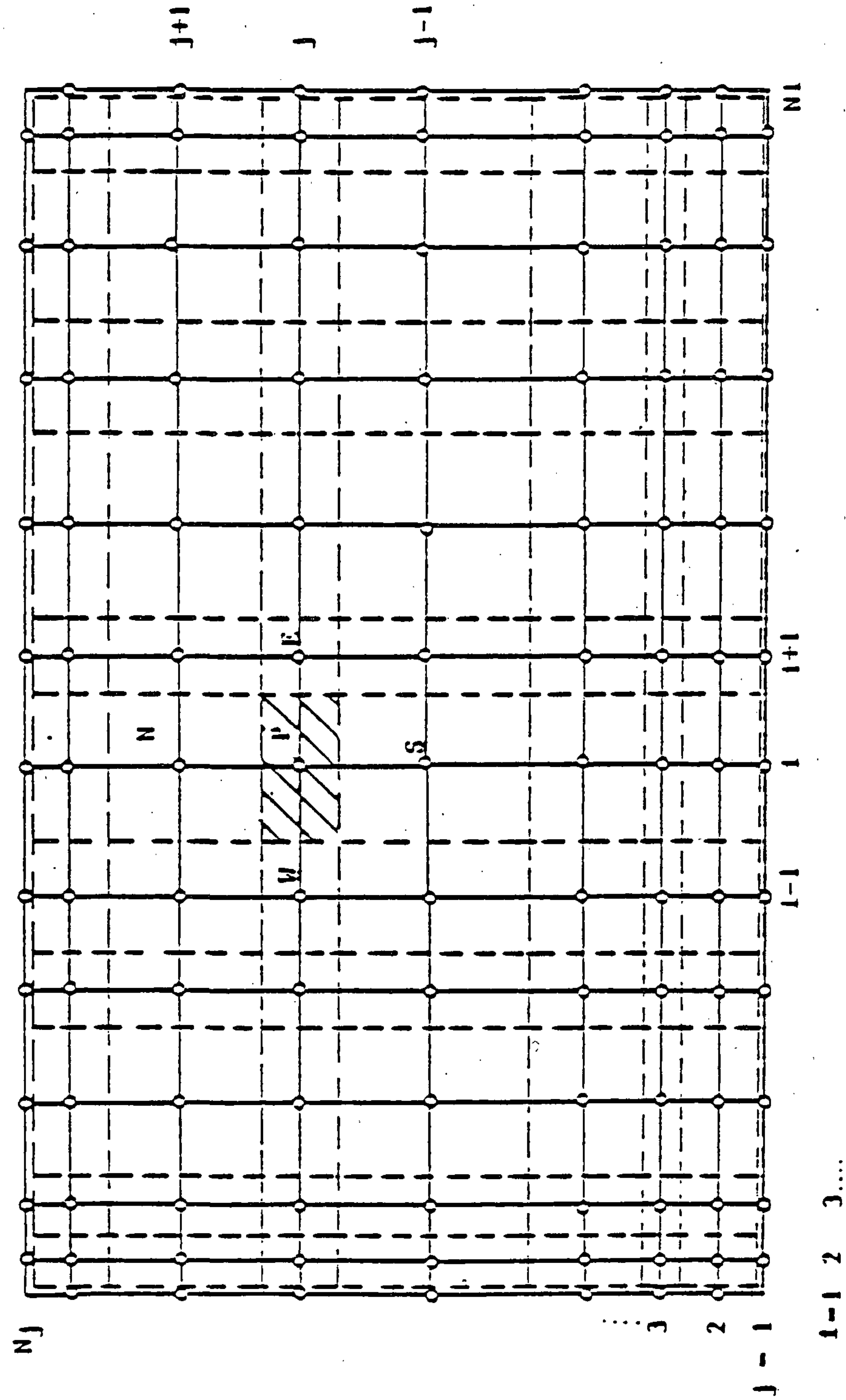
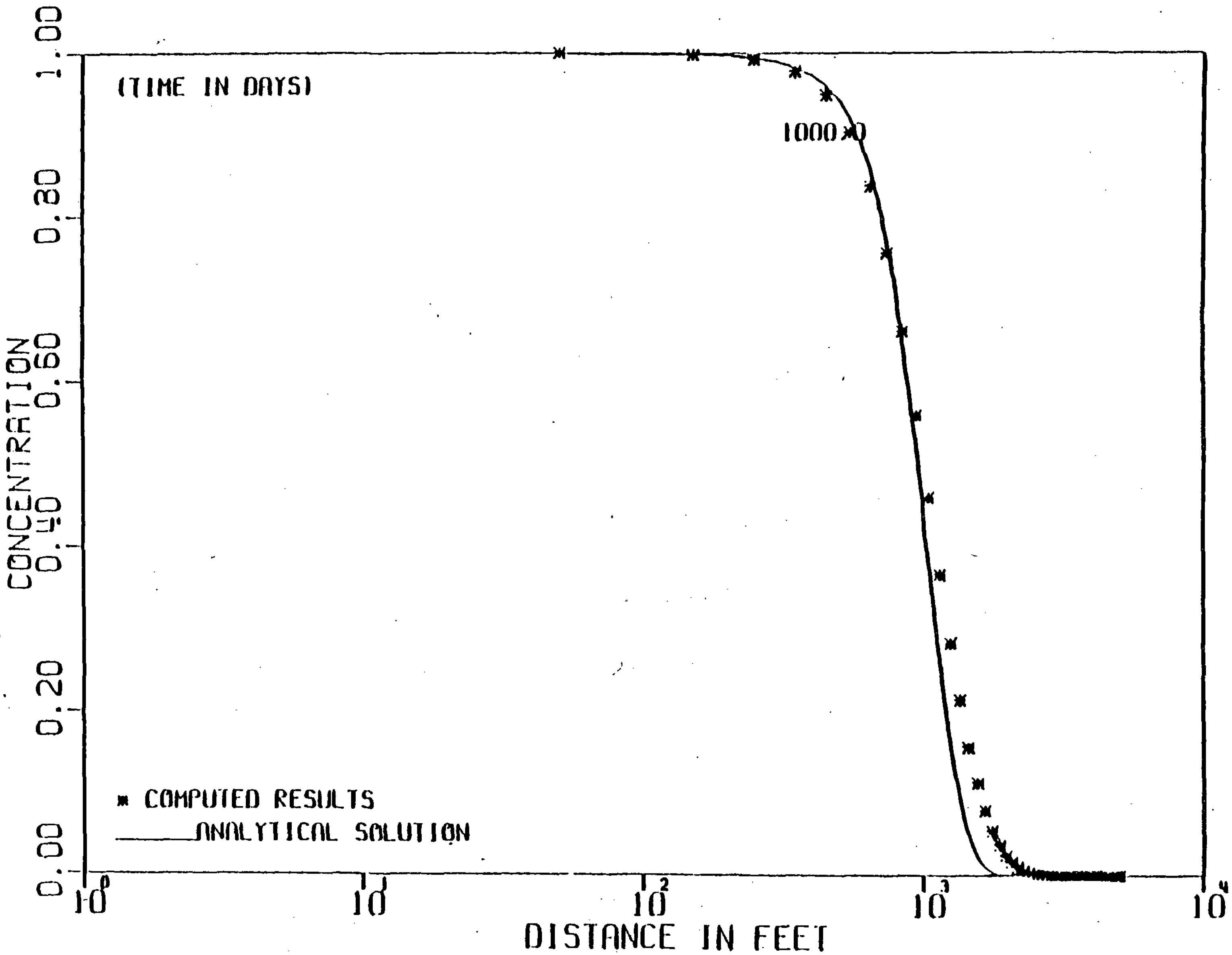
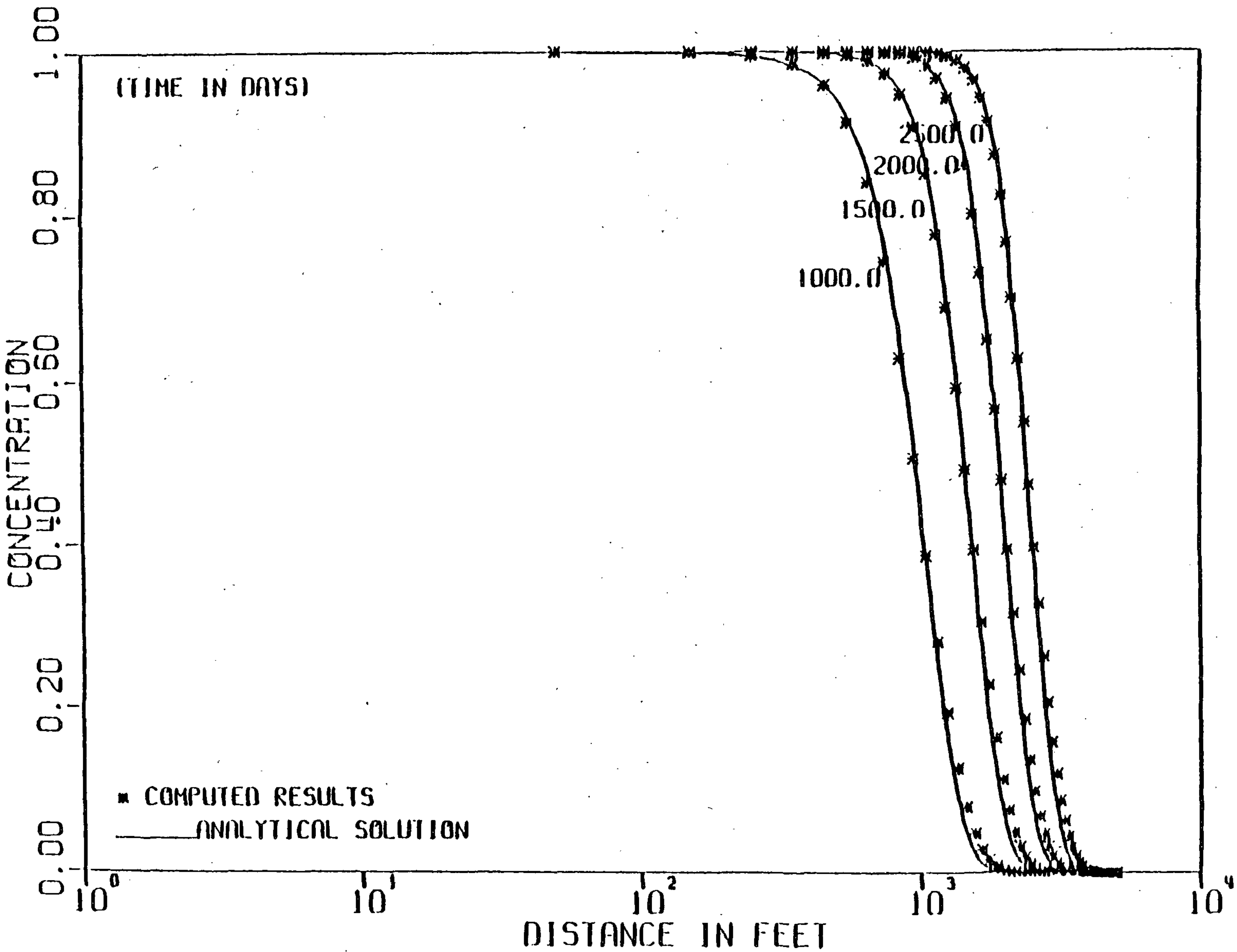


Figure 1

Figure 2



TIME DEPENDENCE OF CONCENTRATION DISTRIBUTIONS



TIME DEPENDENCE OF CONCENTRATION DISTRIBUTIONS

Figure 3

Figure 4

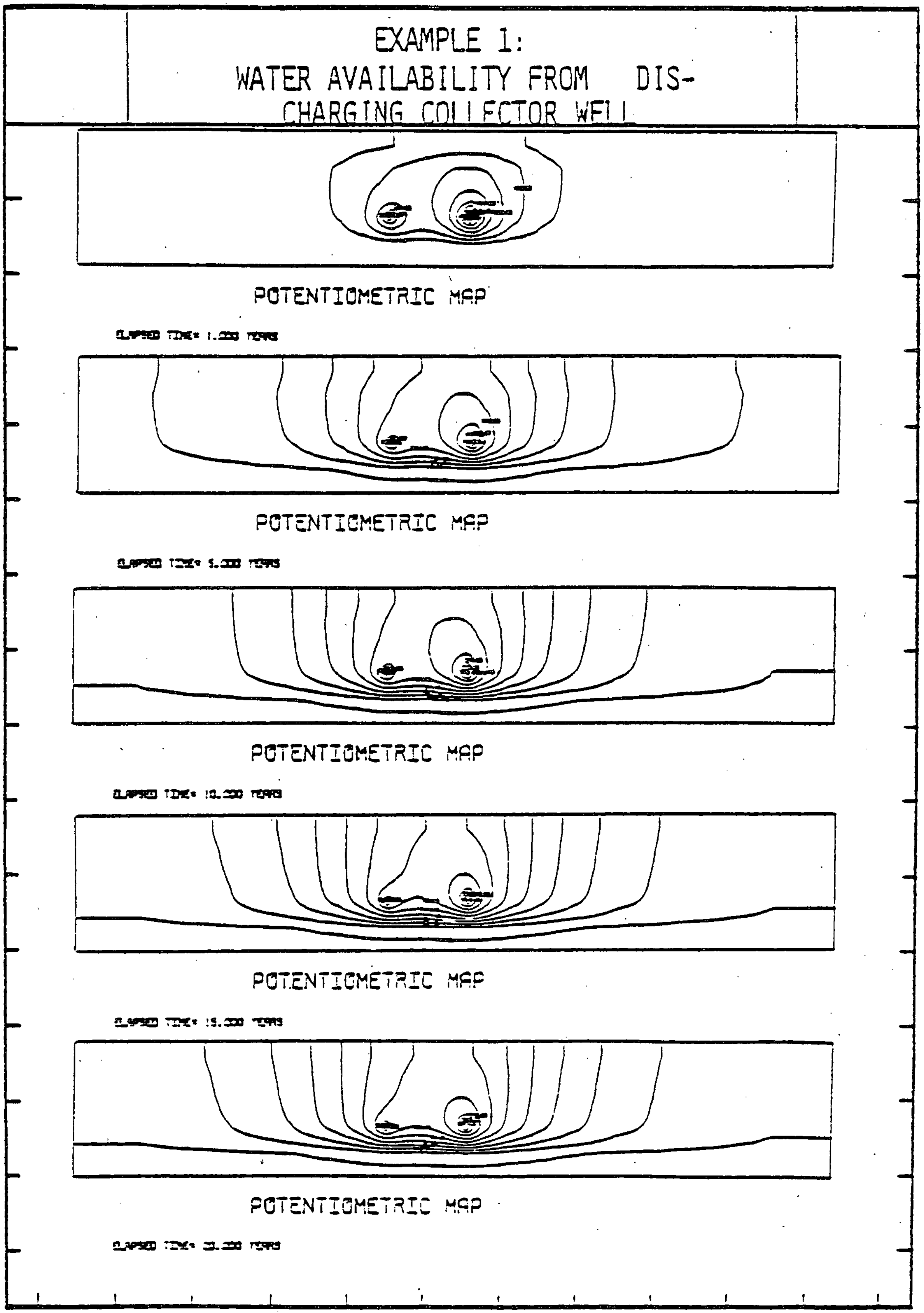

EXAMPLE 1:
WATER AVAILABILITY FROM DIS-
CHARGING COLLECTOR WELL
POTENTIOMETRIC MAP
POTENTIOMETRIC MAP
POTENTIOMETRIC MAP
POTENTIOMETRIC MAP
POTENTIOMETRIC MAP

Figure 5

EXAMPLE 2:
DESIGN OF OPEN-PIT MINE-DEWATERING SYSTEM

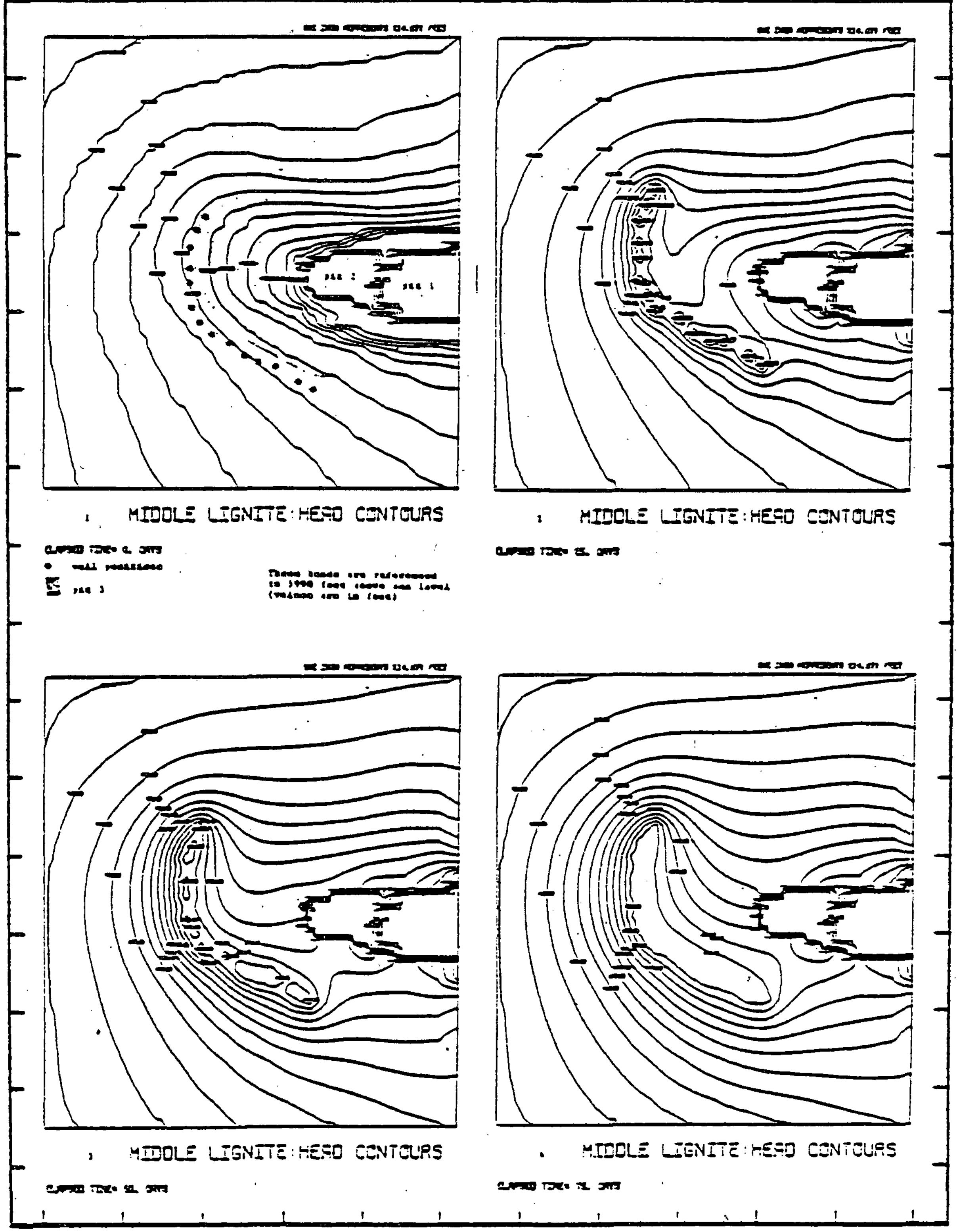
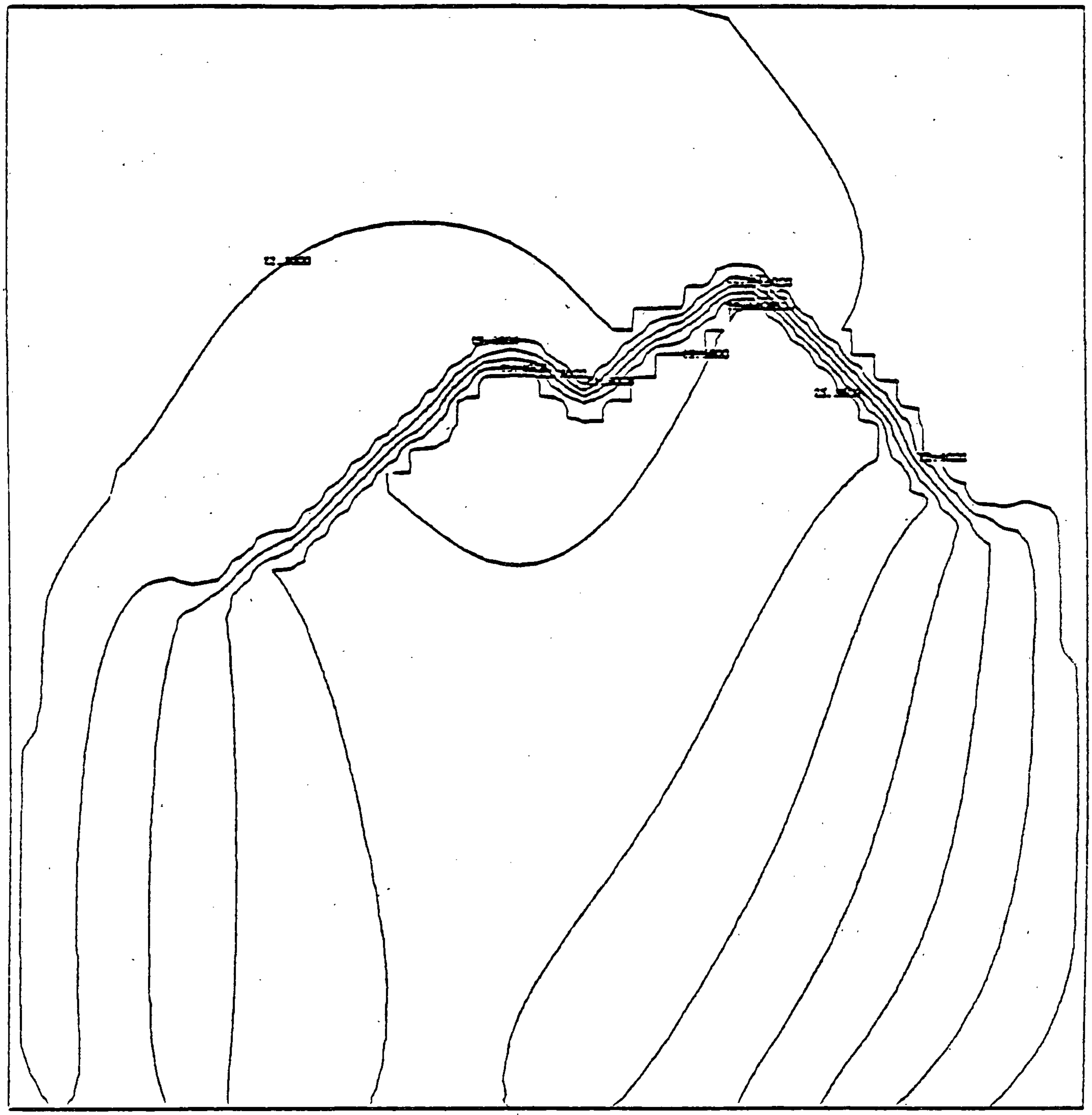


Figure 6: Predicted contours of piezometric heads due to presence of slurry wall



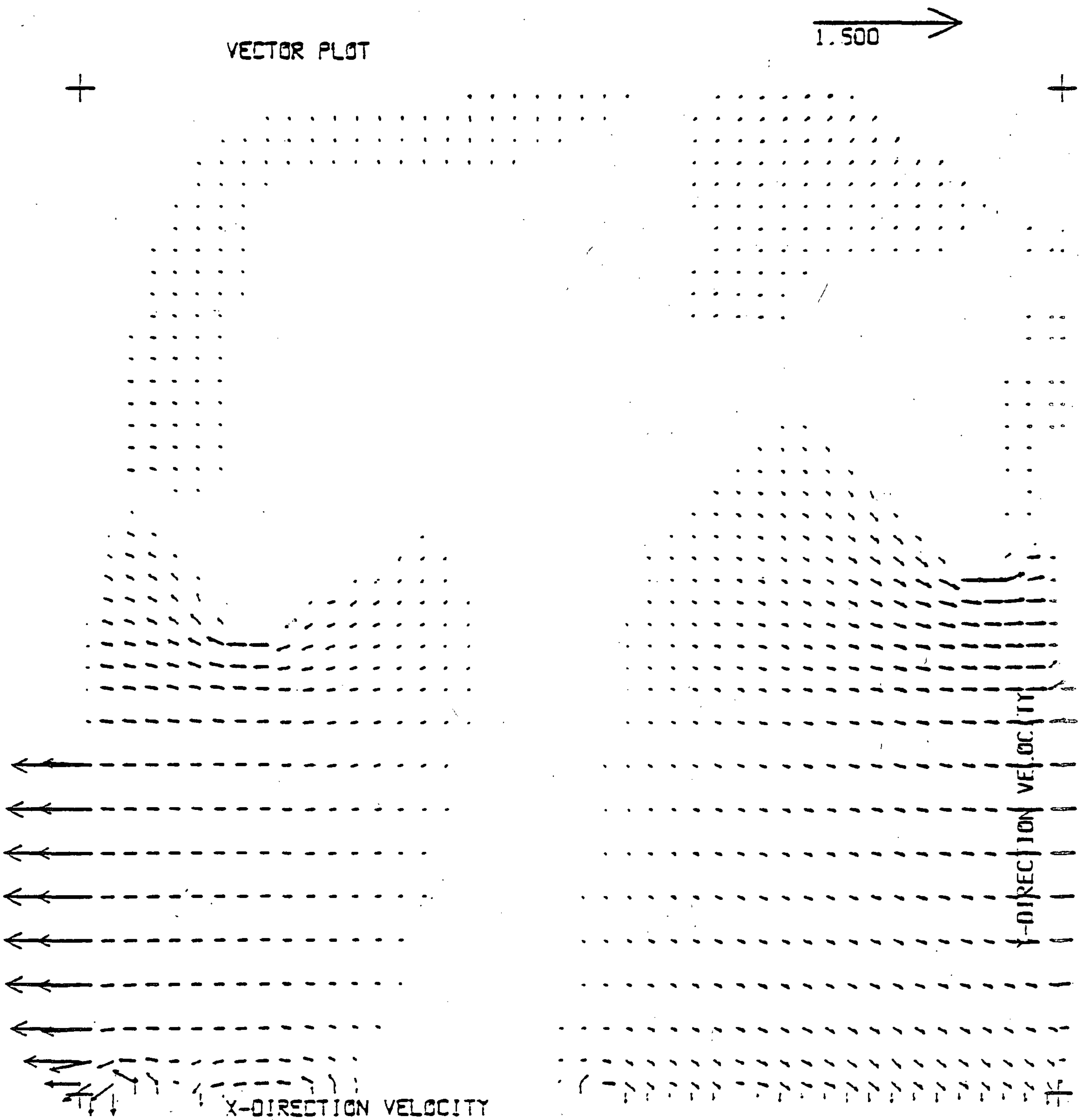
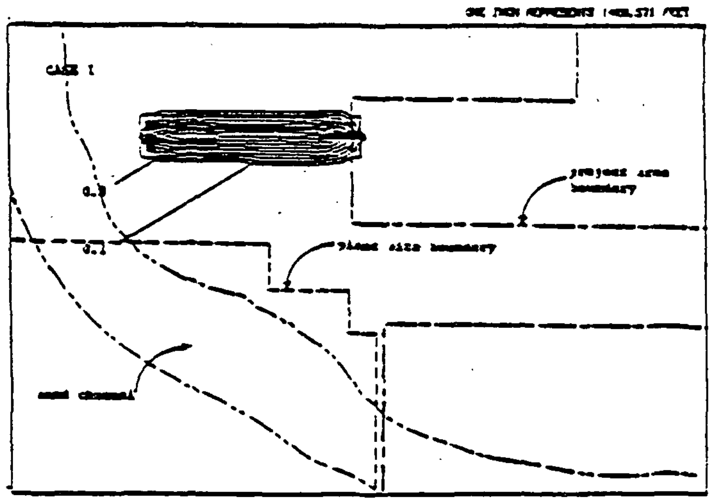


Figure 7: Velocity vectors corresponding to Figure 6.

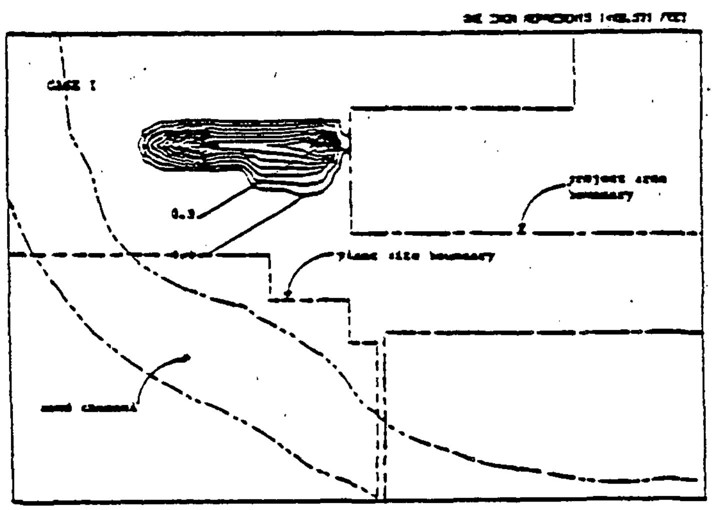
Figure 8a

EXAMPLE 3: CONTD.
CHEMICAL-SPECIES TRANSPORT
D) CONCENTRATION DISTRIBUTIONS



CONTOURS OF CONCENTRATION $\left(\frac{C-C_b}{C_0-C_b}\right)$

TIME= 2 YEARS

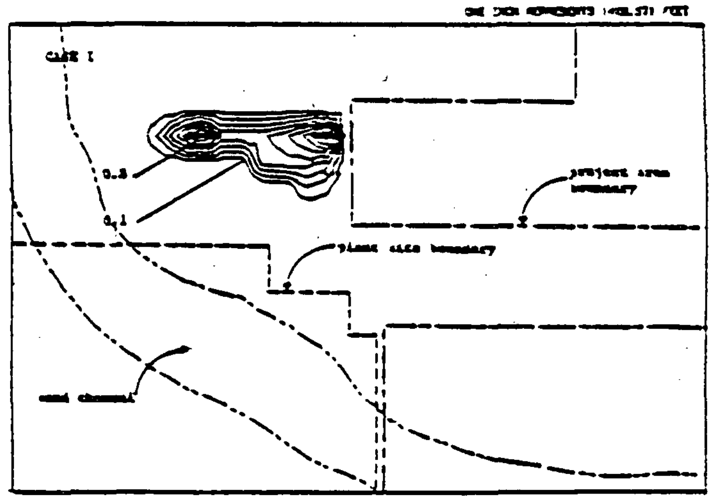


CONTOURS OF CONCENTRATION $\left(\frac{C-C_b}{C_0-C_b}\right)$

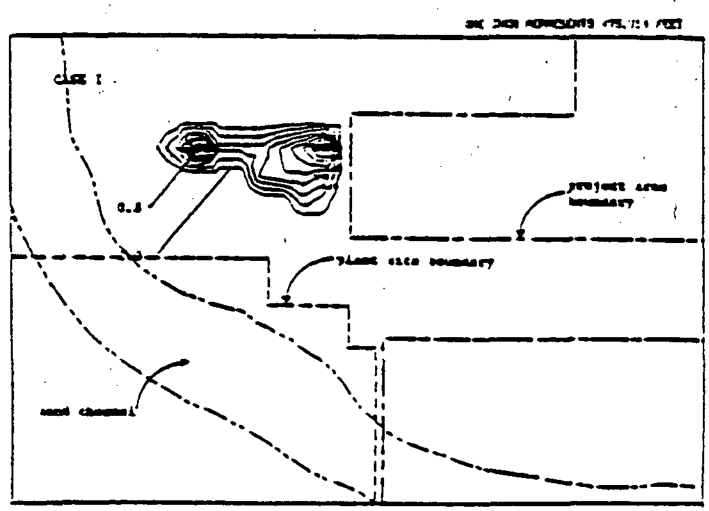
TIME= 10 YEARS

Figure 8b

EXAMPLE 3: CONTD.
CHEMICAL-SPECIES TRANSPORT
D) CONCENTRATION DISTRIBUTIONS



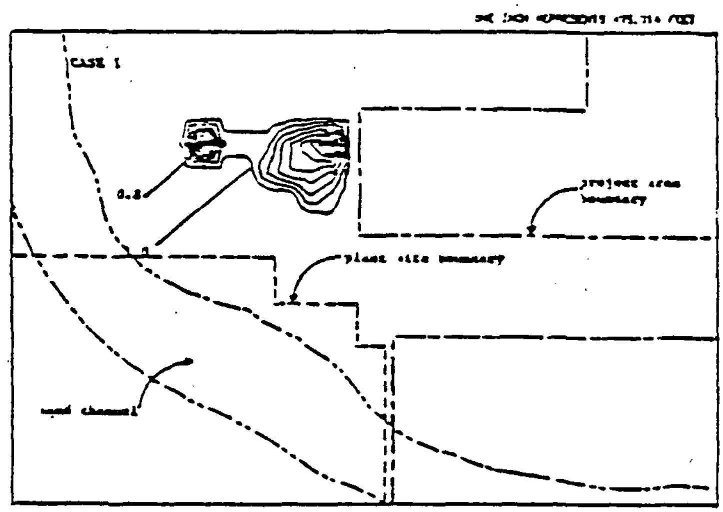
CONTOURS OF CONCENTRATION $\left(\frac{c-c_0}{c_s-c_0}\right)$



CONTOURS OF CONCENTRATION $\left(\frac{c-c_0}{c_s-c_0}\right)$

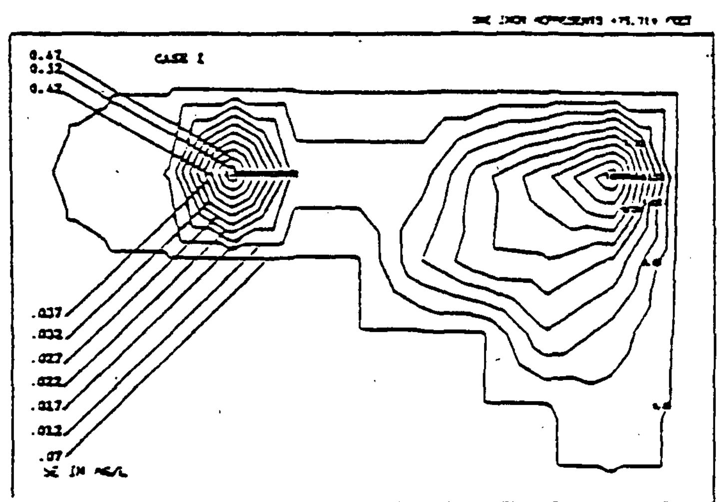
Figure 8c

EXAMPLE 3: CONTD.
CHEMICAL-SPECIES TRANSPORT
D) CONCENTRATION DISTRIBUTIONS



CONTOURS OF CONCENTRATION $\left(\frac{c-c_1}{c_0-c_1}\right)$

TIME= 40. YEARS



CONTOURS OF CONCENTRATION

TIME= 40. YEARS